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CONTENTS

91 **Oil and Transport**
By W. S. Ault

101 **Refining of Lubricating Oils by Chromatography**
By Gyula Nyul and Endre Vamos

109 **Variations with Elevation of Kuwait Reservoir Fluids**
By George Hetherington and A. J. Horan

115 **Relaxation Behaviour of Oils**

119 **Graphical Integration of the Maxwell Fluid Equation and its Application**
By R. F. Crouch and A. Cameron

126 **Obituary: A. C. Hartley, C.B.E.**

Abstracts 495-663

Book Reviews

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THE INSTITUTE OF PETROLEUM

AN Ordinary General Meeting of the Institute of Petroleum was held at 61 New Cavendish Street, London, W.1, on 4 November 1959, the Chair being taken by C. M. Vignoles, C.B.E., President of the Institute.

The General Secretary read the minutes of the previous meeting, which were confirmed and signed as a correct record. He also announced the names of members elected since the previous meeting.

The Chairman introduced Mr Ault, who then presented the following paper in summary.

OIL AND TRANSPORT *

By W. S. AULT† (Fellow)

INTRODUCTION AND BACKGROUND

ACCORDING to the Annual Report of the British Transport Commission for 1958 out of every £1 of personal expenditure elevenpence were spent on private motoring, twopence on rail travel, and sixpence on other forms of travel. In a very simple way these figures give us an immediate picture of the importance of the transport industry in the economy of the country.

To keep the length of this paper within reasonable bounds the author has found it necessary to confine himself primarily to transport within the British Isles; however, where appropriate, some indication has been given of what might be called export business in transport.

Expanding the brief summary of personal expenditure on transport given above, the following general information is relevant.

Employment

Approximately 3½ million people are employed in the British transport industry, amounting to about 15 per cent of the working population. Of this total some 1·8 million are concerned directly with provision of transport services, and 1·7 million are engaged in the manufacture and repair of vehicles, aircraft, and ships, the construction and maintenance of roads and railways, and the provision of ancillary services.

Within this framework large employers are the following:

TABLE I

	Workers
British Transport Commission	774,000
Road transport, excluding British Road Services	910,000
Motor vehicle manufacturers	323,000
Aircraft manufacturers	243,000
Shipbuilding	193,000

The number of workers quoted for the aircraft industry does not take into account recent reductions in this sector.

Fixed Capital Investment

The latest figures available show that in 1957 capital investment in transport and its ancillary services was some 16 per cent of the national total, made up as follows:

TABLE II

	£ million
Railways	127
Road passenger transport	22
Shipping	128
Harbours, docks, and canals	17
Air transport	57
Road goods transport	150
Roads, including public lighting	38
Total	539

Production

Production figures for 1958 were at the following levels:

TABLE III

Motor industry	
Cars	1,051,550
Commercial vehicles	312,850
Motor cycles, scooters, and three-wheelers	over 144,000
Aircraft industry	
Piston-engined aircraft	140
Turbine-engined aircraft	336
Railway locomotives and rolling stock	
Diesel locomotives	958
Steam locomotives	105
Coaches	over 2,500
Goods wagons	almost 42,000
Shipbuilding	
Gross tonnage completed	1·4 million
Gross tonnage on order	5·4 „

Export of Transport Equipment

In 1958 exports of transport equipment totalled £581 million, amounting to 18·3 per cent of total

* MS received 27 October 1959.

† Shell-Mex and B.P. Ltd.

exports of £3171 million. The transport total was made up as follows:

TABLE IV

	£ million
Motor vehicles	330
Aircraft and aero engines	142·5
Railway vehicles	46·3
Ships	63·1
Total	581·9

The pattern of communication, and hence of transport, in any country is primarily determined by its geography and the state of its economic development. In Britain distances are comparatively short, and the country is highly developed. Consequently, although coastal shipping, air, and inland waterways all play a part, surface transport is in a pre-eminent position. The following two tables taken from a survey made in April 1958 by the Ministry of Transport and Civil Aviation illustrate this and also show the changes in the contributions made by road and rail between 1952 and 1958.

TABLE V

Domestic Goods Transport, 1958

	Tons carried, millions	Ton miles, thousand millions	Proportion of total per cent	
			tons	ton miles
Road	1000	23	76	45
Rail	260	18	19	35
Inland waterways	10	—	1	—
Coastal shipping	50	10	4	20

The contribution of air transport, 9700 tons, is too small for inclusion in the above table.

TABLE VI

Inland Goods Transport, 1952 and 1958

	Ton miles, thousand millions		Per cent of ton miles	
	1952	1958	1952	1958
Road	18·8	23·1	46	56
Rail	22·4	18·3	54	44
Total	41·2	41·4	100	100

TABLE VII

Domestic Passenger Traffic, by Public Services, 1958

	Passenger journeys, millions	Passenger miles, millions
Railways, less London Transport Executive	1,090	21,725
LTE	692	3,300
Total rail	1,782	25,025
Road, less LTE	11,374	41,330
LTE	2,484	5,597
Total road	13,858	46,927
Air	1·5	302
Total	15,641·5	72,254

If inland waterways and coastal shipping are excluded it is possible to make a direct comparison of the contributions made by road and rail over a six-year period.

TABLE VIII

Petroleum Fuels used in Transport, United Kingdom

	Motor spirit, thousand tons
Road	
Cars and motor cycles	3,636
Commercial transport of passengers and goods	2,765
	Derv, thousand tons
Passenger transport	825
Goods transport	1,224
	Gas oil, tons
Rail	80,000
Air	
Total consumption of all aviation fuels 1,565 thousand tons	
Inland waterways and coastal shipping	Gas oil and diesel grades, thousand tons: 252 — Fuel oil grades, thousand tons: 684

THE PETROLEUM INDUSTRY AS A USER OF TRANSPORT

Within the U.K. the petroleum industry uses coastal tankers, tank barges on inland waters, rail tank cars, and road tank wagons for the transport of the greater part of its products. Pipelines are also used where the quantities required and the concentration of demand are sufficiently high to justify this method.

Supplies of crude in general arrive at the refineries by large ocean tanker, and consequently do not enter into the domestic transport picture.

In 1958 the ton/mileage involved in the domestic movement of petroleum products was about 4000 million, and excluding the contribution of inland waterways represented over 7 per cent of the total ton/miles transported by road, rail, and coastal shipping in that year.

THE EMERGENCE OF PETROLEUM FUELS FOR TRANSPORT

Until the practical realization of nuclear power, fossil fuels were the only source of energy for transport which was available on a sufficiently large scale for continued use. Admittedly wood was used in some remote parts of the world, but the forests of the world could not have met the demand once rail transport had become a part of life, any more than the forests of Great Britain could for long meet the demands of the iron founders.

The use of coal preceded the discovery of oil in commercial quantities by many years, consequently the steam locomotive and the ship's boiler were originally developed around coal. As a result, the steam

locomotive has never been a happy subject for direct conversion to oil firing, although this has been done in some countries where oil is readily available and coal is not, pending arrival of the diesel locomotive to displace steam completely.

Apart from marine use, and the few steam locomotives using oil, the connexion between petroleum fuels and transport stems essentially from the invention of the internal combustion engine. Historically it is interesting to recall that this was originally produced to use coal gas, but in this form it was tied to the gas mains, and its use for transport could make no progress until a portable fuel, in fact petroleum, was available in quantity.

However, there are two basic reasons, unconnected with the internal combustion engine, which have weighed heavily in the choice of petroleum fuels for transport, the first being that they are liquid and the second that the energy they contain is in fairly concentrated form. It therefore follows that the fuel supply can be carried in more or less any part of the vehicle or vessel and can be rapidly recharged without appreciable manual labour. Furthermore, supplies are available in enormous quantities at reasonable cost.

These considerations apply whether the fuel is to be used in a steam plant or in an internal combustion engine, and explain the rapidity with which the use of oil fuel developed in shipping, starting with the Royal Navy just before and during the first world war and being followed after that war by merchant fleets. Modern naval operations would be inconceivable in terms of coal, except possibly by the use of pulverized coal, which would bring many fresh difficulties and hazards.

The fundamental reason why the internal combustion engine has become linked to petroleum fuel is that from its basic nature it has no reserve of energy available for immediate use by expansion, like the energy stored in the boiler of a steam engine. Consequently it requires a fuel which can be metered, immediately and accurately, to meet the varying load on the engine. This requirement can be met readily only by a liquid or a gas, and in practice the difficulty of storage rules out gases for transport applications. Theoretically, other liquids, such as alcohols, could be used as fuel for internal combustion engines, and in special circumstances alcohols are so used, but in general the ready availability and reasonable cost of petroleum fuels have left them unrivalled.

THE DEVELOPMENT OF THE INTERNAL COMBUSTION ENGINE

In the field of transport the original reasons for choosing the internal combustion engine, rather than the steam plant, were essentially its portability, its good power/rate ratio, and the fact that it could readily be made in units giving the fairly low outputs which were needed. These factors alone made it the natural choice as the power unit for the early road vehicles and aircraft, and initially the chief preoccupation of designers and users was to achieve a reasonable standard of reliability. It was not until considerably later that questions of thermal efficiency, and hence of fuel consumption, began to influence the development of the internal combustion engine. It is outside the scope of this paper to discuss thermal efficiency and engine development in any detail. For our purpose it is sufficiently accurate to state that the higher the compression ratio of an internal combustion engine, whether petrol, diesel, or gas turbine, the higher will be its thermal efficiency, and hence the lower its fuel consumption for a given amount of work done.

Although thermal efficiency even to-day is by no means the only consideration influencing the choice of engine for transport applications, it seems convenient at this stage to discuss the effects it and other factors are having on the various fields of transport. At the same time it will be convenient to consider the directions of future development.

RAIL TRANSPORT

Compared with the steam locomotive, the much higher practical thermal efficiency of the diesel, coupled with its ability to work more hours per day, gives lower running costs, which more than offset the higher first cost, the higher cost of the fuel, and in some respects increased maintenance charges. Already starting at a lower thermal efficiency than the diesel, the efficiency of the steam locomotive is still further reduced in practice by the continuing consumption of fuel when it is at rest, a factor which is particularly important in shunting engines, and contributed heavily to the adoption of the diesel shunter in the U.K. before any progress was made with main line diesels. As the recent report on modernization of British Railways clearly shows, the steam locomotive can be disregarded for the future, in which electric, diesel, and gas turbine power units will rival, but to some extent supplement, each other. Given sufficient traffic density, such as applies in many parts of the Southern Region of British Railways, the British Transport Commission considers that electrification is justified in spite of the heavy capital charges involved in laying or converting electrified track, together with that of the transformers, transmission lines, sub-stations, and switchgear which are still required, even though the source of supply is the National Grid.

The following working costs taken from the 1958

Report of the British Transport Commission are interesting:

TABLE IX

	1958, loco-hauled train working costs, per train/mile		
	Steam s. d.	Diesel s. d.	Electric s. d.
Enginemen and motormen . . .	1 11·4	1 1·5	8·2
Fuel and power for traction, heating, and lighting . . .	3 1·1	6·1	2 9·1
	5 0·5	1 7·6	3 5·3

On most of our rail routes, however, traffic does not reach this density and besides the imperative need to modernize there is the almost equally important consideration that this should be done with the minimum disturbance to existing traffic. Here the diesel, both as a locomotive and as the power unit for railcars, scores heavily, since apart from providing fuel storage and special maintenance facilities, neither of which is very onerous, the new units can be put into operation as soon as they are available.

The quantitative picture of the future of British Railways, as regards adoption of the diesel and hence of petroleum fuels, is available from the reports of the British Transport Commission. We should, however, consider what qualitative changes are likely in the future, especially those which could affect the type of fuel needed.

The diesel engine, in the size ranges used in locomotives, is basically similar to engines which have been made for many years, and the development of new engines with markedly different fuel requirements seems unlikely. Turbo-charging, and its ultimate conclusion the free-piston engine, also the gas turbine, all tend theoretically towards less selectivity as regards the fuel. The possibility of using cheaper, part-residual fuels has therefore attracted some interest, notably in the U.S.A., where several railroad companies have carried out tests and one line continues to use a part-residual fuel. The general view, however, seems to be that the increased complication on the locomotive of heating facilities and arrangements for changing from a distillate fuel to the part-residual fuel and back again with changes in load, together with a significant reduction in engine life between overhauls, more than outweigh the savings in fuel cost. Under British conditions of shorter average hauls and denser traffic the use of part-residual fuels seems even less attractive.

As in most of its transport applications, except the air, progress of the gas turbine on the railways has disappointed its enthusiastic supporters. Basically the difficulty is its inability, unlike the diesel, to maintain high efficiency at part load without the use of fairly bulky and troublesome heat exchangers. This loss of efficiency where there is appreciable part-load running, as on the railways, would be less important if it were able to use heavy residual fuels. Although gas turbines are operated successfully on heavy fuels, there are still serious difficulties in using them in the size of turbine called for by locomotives. However, in many ways the gas turbine is an attractive power unit for railway traction, and we must expect its supporters to continue their strenuous efforts to overcome the difficulties in applying it to this purpose.

The power units of the railcars, or power coaches as they are now more generally called, are basically derived from truck engines, which demand a good quality distillate fuel if they are to give satisfactory operation. They and the locomotives appear well satisfied with the distillate fuel they are using at present, and it seems unlikely that any changes in quality will be necessary.

ROAD TRANSPORT

There appears to be no slowing up yet in the steady increase in compression ratios of spark ignition engines as fitted to private cars. In fact, the recent launching of new models by the Rootes Group and Fords with compression ratios of 9·2 : 1 and 8·9 : 1, respectively, suggests that we are about to see a definite step forward by British manufacturers which will bring them on average considerably closer to their American counterparts. The highest compression ratio so far used in any production model of British manufacturers is 10 : 1, so that current super fuels of 100 research octane rating can meet present octane requirements and seem likely to do so for some little time. Historically, octane number and compression ratio have advanced side by side since the earliest days of the petrol engine, and there is no reason to suppose that this will stop. There are, however, two factors which have become important only in recent years which might well affect the rate of further increase in octane number. The first is that in the British market the anti-knock quality offered by the super fuels still leaves a margin for further engine development in the ordinary family car. The second is that at compression ratios of just over 10 : 1 American engine builders have run up against the problem of rumble. This combustion abnormality, the precise mechanism of which is still under investigation, although it is undoubtedly a form of surface ignition, makes itself evident by a distressing rumbling noise from the bearings, and can lead to mechanical damage if allowed to persist. The use of phosphorus additives in the fuel is a valuable palliative, but they are not a complete cure, nor are they universally used. Consequently, since rumble has already appeared in cars

in production in the U.S.A. the American designer has found it necessary to call at any rate a temporary halt to further increases in compression ratio, and in some cases has made a slight reduction. So far the problem of rumble has not affected production engines in Britain, but it is a possible obstacle which cannot be ignored.

Conversion of road transport from petrol to diesel engines continues, although most of the more profitable conversions, the heavy vehicles and passenger buses, have been diesel-powered for many years, leaving for consideration the more marginal cases of the light commercial vehicle and the passenger car. The development of the road diesel between the two world wars was initially helped by fiscal preference, but since 1935 the tax levels on petrol and derv have been the same, and the case for the diesel has rested largely on its inherently higher thermal efficiency. The practical results of this are illustrated by the following table, which shows the cost per brake horsepower/hour for engines using various fuels. The compression ratios shown must be regarded purely as typical, and the actual ratio that can be used for any particular fuel is influenced considerably by engine design.

TABLE X

	Petrol			Derv
	Regular	Premium	Super	
Typical compression ratio usable. .	6·5 : 1	8·5 : 1	10 : 1	16 : 1
Retail price per gallon, including tax.	4*s.* 3*d.*	4*s.* 8½*d.*	4*s.* 11½*d.*	4*s.* 4½*d.*
Cost per BHP/hr at maximum engine output . .	4·14*d.*	3·95*d.*	3·66*d.*	2·37*d.*
Cost per BHP/hr at half engine output	4·35*d.*	4·18*d.*	3·89*d.*	2·25*d.*

As regards the increase in capital cost and weight incurred by the user, this varies considerably with the particular vehicle. However, taking current diesel engines which are alternative to petrol engines for a five-ton truck and for a light van, typical figures are:

TABLE XI

	Additional weight	Additional first cost
Five-ton truck	274 lb	£185
Light van	56 lb	£176

Most heavy vehicles cover high annual mileages, and fuel cost is a major item, hence the almost universal use of the diesel for many years now. The user of light commercial vehicles must, however, study more carefully how the saving in fuel cost relates to the rate at which he is prepared to amortize the increased capital investment. He will also need to consider whether in his case there is likely to be a significant difference in maintenance costs between otherwise equivalent petrol- and diesel-engined vehicles, about which there is considerable difference of opinion. Certainly the diesel requires more specialized maintenance, which may be more expensive, but against this the working life of the engine tends to be greater. A further factor favouring the diesel is its much better fuel economy when idling and at light load, an extreme case of this being the London taxi, where a petrol-driven cab will typically do 17 mpg, whilst its diesel-driven equivalent increases this to 34 mpg, a much greater saving than would be predicted from the straightforward thermal efficiencies.

In the U.K. the diesel-powered passenger car has achieved negligible success, although a number of technically suitable engines are available and there are several makes of diesel car in regular production in other countries. Admittedly many cars cover a quite low annual mileage, so that it would take four or five years' fuel savings to recover the increased capital cost, as compared with about one year for the London taxi, but equally many business cars cover annual mileages of the order of 20,000, and would therefore seem to present a case for the diesel. The author's view is that the reason lies in the lower "amenity value" of the diesel engine as at present applied to passenger cars. Such as he has tried are noticeably rougher and noisier than their petrol-engined counterparts, and the restricted speed range of the diesel compared with the petrol engine sets a limit to the performance which can be obtained with a simple transmission system. Doubtless these defects could be overcome by intensive work on sound insulation and the development of a more elaborate multi-speed transmission, preferably stepless, but so far no manufacturer seems to have felt that the sales results would justify the considerable development expenditure which would be required.

As compression ratios increase, the problems with which the designer of petrol engines has to deal become similar to those involved in the diesel. Scantlings of components have to be increased and the whole engine made stiffer to deal with increased combustion pressures and bearing loads, so that the basic structure of the high compression spark ignition engine becomes closely similar to that of the diesel, and in fact common crankcases, cylinder blocks, and other components are already used by a number of manufacturers. Consequently, apart from the inherently rather costly fuel injection equipment, the basic cost of the two engines is about the same, so that the two main problems to be overcome remain noise and restricted speed range.

Although at present it seems unlikely, any widespread conversion of passenger cars to diesel power units would make it exceedingly difficult for the oil industry to provide the present type of derv fuel in the quantities which would be needed, in addition to meeting current demands for middle distillates for

other purposes. At the same time, there would be a surplus of naphthas falling within the gasoline boiling range. Clearly, such a widespread conversion would take several years to have a significant effect, but if it did come about it would probably be necessary to provide a fuel of much wider boiling range, which would include the naphthas which would otherwise have gone to the production of gasoline. Although of lower specific gravity and therefore yielding less miles per gallon than the present derv, the new fuel, having a higher volatility, should improve combustion at higher engine speeds and by allowing maximum engine speeds of the small diesel to be raised make it more competitive with the petrol engine for use in passenger cars. A fuel of this type would also be eminently suitable for the gas turbine car when it appears in production, as distinct from prototype form.

MARINE TRANSPORT

Setting nuclear energy aside for the moment, one thing seems certain in the future of marine transport —that the preferred fuel will continue to be oil.

The period between the two world wars marked the emergence of the diesel to a position of major importance as the main engine for ocean-going ships. This position was gained very largely by virtue of its markedly superior thermal efficiency, hence lower fuel consumption, as compared with the current steam plants. Since the second world war further impetus has been given to the diesel by its ability to burn the cheaper boiler grades of marine fuel oil, a development in which the oil companies have done considerable original work in their own tanker fleets.

However, in recent years considerable improvement has also been achieved in the thermal efficiency of steam plants by the adoption of higher steam pressures and temperatures, which have brought the efficiency of the modern steam turbine plants not far behind that of the diesel. The table below gives typical fuel consumptions for main engines of modern design.

TABLE XII

	Lb fuel/shaft hp/hr
Supercharged diesel	0·34
Steam turbine	0·53
Gas turbine	0·60

For those ships which, because of their size or high service speed, require main engines of high total output, the oil-fired steam turbine plant remains the first choice. Considerations of turn-round time and percentage availability for service can also influence the choice of power plant, since with steam plants it is often possible to prepare boilers for inspection and overhaul whilst the ship is still at sea, whereas partial preparation ahead of docking is impossible with the diesel.

The gas turbine has been a slow developer in the marine world, in spite of considerable work, including operation by the Shell Group of the experimental tanker *Auris*. The results obtained on this ship, although satisfactory technically, have not been encouraging economically. A special application of the gas turbine, which has shown considerable promise, is the small high-speed naval craft, for which the high output of the gas turbine for a given bulk and weight has peculiar advantages. For civilian small craft the diesel is virtually without a rival, combining as it does excellent fuel economy with economy in engine room staff.

Although the three types of power plant mentioned above must continue to be the object of further development and improvement, it seems unlikely that developments will call for any drastic changes in fuel quality.

AIR TRANSPORT

In spite of the rapid progress of the pure jet and propeller turbine, there are still vast numbers of piston engines flying and likely to continue doing so for at least ten years. As the major airlines complete their programmes for re-equipping with propeller turbine or pure jet aircraft, we shall see a substantial number of piston-engined aircraft of recent design coming on to the second-hand market and continuing to require advanced piston engine fuels of the type of 108/135 and 115/145 Avgas. However, further development of the piston engine seems most unlikely, so that fuels of the grades mentioned should be adequate to take care of piston-engined aircraft for the rest of their life. Nevertheless, the study of alternative anti-knock compounds continues and should provide fuels of even higher performance should a demand arise.

The rivalry between the pure jet and the propeller turbine continues and is influenced by factors such as prestige and the passenger appeal of speed as well as by sheer economics. However, a pattern now seems to be emerging in which the large pure jet is the choice for long distances, the shorter hauls being handled by the propeller turbine aircraft. In the military field there is no immediate alternative to the pure jet for combat aircraft, although we may expect to see rocket motors and possible ramjets supplementing at high speeds the thrust of the main turbines. Military transport aircraft, for which sheer speed and service ceiling are not the prime requirements, may be expected to use propeller turbines.

As far as petroleum fuels for aviation are concerned, the picture seems to comprise a gradually declining demand for piston engine fuels, the rate of decline depending greatly on the development of "second line" civil air transport based on second-hand aircraft. Simultaneously we must expect a steady in-

crease in the demand for turbine fuels. At present the kerosine type fuel, Avtur, is the general choice of the civilian operator, military aircraft using the wide range fuel Avtag, which is considerably easier to manufacture in large quantities. At present both military and civil requirements seem to be met satisfactorily by current qualities of these fuels, but we may expect to see a small demand for specialized petroleum fractions to meet the needs of very high-speed aircraft and the rocket motors of ballistic missiles.

THE MANUFACTURING PICTURE

To attempt to give a detailed picture of the effects that changes in the use of petroleum fuels for transport will have on refinery planning must be outside the scope of this paper. Nevertheless, the following trends are clear.

Motor Spirit

It is expected that the steadily increasing demand for premium motor spirit will continue and will include an increasing proportion of the super-premium quality as engine builders continue their progress towards higher compression ratios. Whether there will soon have to be an increase in the octane rating of the super-premium grades must depend on how successful engine designers are in overcoming the difficulties attendant on compression ratios of over 10 : 1 which were mentioned earlier, and also on the cost of additional octane numbers. However, the increase in the proportion of premium grades sold will, in itself, increase the average octane level of total motor spirit production, which must be reflected in changes in the balance of existing refinery processes or in their severity. The processes which seem most likely to be concerned are the various types of catalytic reforming, which avoid diversion to gasoline of middle distillates needed for other purposes.

Some gradual increase in the TEL content of motor spirit seems likely and should not cause difficulty with engines of modern design.

Derv

Although a sweeping conversion to the diesel for road transport seems improbable for reasons given earlier, the demand for derv and other distillate diesel fuel must be expected to increase. Current ignition quality and sulphur level seem to be generally acceptable, and demands for further reduction in sulphur content or increase in ignition quality, coupled with a steady increase in quantitative demand, could cause increases in manufacturing costs which would in the end have to be borne by the user.

Fuel Oils

In many parts of the world to-day the use of the heavier fuel oils for marine bunkers is overshadowed by the rapidly increasing demands of stationary plants, steel making, and general furnace use. Consequently, fuel oil production has to be considered as a whole and in relation to the required output of other products. It seems unlikely that any new problems connected with the use of fuel oil in transport will arise.

POSSIBLE REVOLUTIONARY DEVELOPMENTS

Nuclear Power

For ships, nuclear power is already a reality, although the capital cost of the power plant is at present so high as to confine its use to special applications, such as submarines and the new Soviet icebreaker, *Lenin*. It seems unlikely that this situation will change rapidly, although the peculiar advantages of nuclear power plants for possible commercial submarines cannot be overlooked. Nevertheless, it appears that the great majority of the world's merchant shipping will continue to use petroleum fuels for many years to come.

For aircraft, nuclear power at first sight appears to have considerable attractions for military purposes. However, a practical power plant, when eventually produced, will almost certainly be immensely costly, and the author believes that similar results could be achieved more economically and with greater flexibility by the extensive use of in-flight refuelling.

For transport on land the only foreseeable use of nuclear power would seem to be via electricity drawn from the National Grid.

Fuel Cells

Research into fuel cells is going on in several countries, including Great Britain. Most of the work done so far has been with hydrogen and oxygen as the fuel and oxidant respectively, but the use of petroleum fuels is also being studied. Although, theoretically, there would be no difficulty in preparing hydrogen and oxygen by electrolysis of water, given an adequate supply of electricity at a very low cost per unit, the practical difficulties of storage and distribution would be immense. Consequently, it seems reasonably certain that any practical application of the fuel cell to transport would employ a liquid petroleum product as the fuel. The prize to be won by the development of a practical fuel cell is considerable, since it appears to be the only way of getting round the thermodynamic principles which limit conventional heat engines to a thermal efficiency of about 40 per cent.

ACKNOWLEDGMENTS

The author would like to express his gratitude to the directors of Shell-Mex and B.P. Ltd for their permission to present this paper and to his colleagues who have helped in its preparation.

DISCUSSION

A. T. Wilford: I am pleased to have the opportunity of opening the discussion on Mr Ault's paper, which gives an impressive account of the contribution which oil has made to transport. It is interesting, though somewhat profitless, to speculate on the pattern which transport might have assumed had oil been first produced in commercial quantities in, say, 1959 rather than 1859. There would presumably have been little or no development of air transport; the railways would not be bemoaning the loss of freight traffic to roads; electric trams and trolley-buses would, no doubt, have served the needs of urban passenger transport as they do to-day in Europe, but what substitute, if any, there would have been for individual private transport is difficult to imagine. All that can be said is that the investment in the automobile industry and its product would have been sufficient to provide some startling innovations.

When accepting an invitation to open the discussion I had expected that my remarks could be confined to matters within my own province, but I cannot escape from having to comment on Table IX. The figures quoted are correctly extracted from the 1958 Report of the British Transport Commission, though they refer not to loco-hauled trains as stated in the heading of the table, but to steam, diesel, and electric traction respectively. At their face value the figures imply that working costs per train mile for diesel traction are less than one-half those for electric traction, as indeed was the case during 1958. The point is, however, that the comparison between the two forms of traction is not a valid one, in that like is not being compared with like. The figures give an overall picture of train working costs and include loco-hauled passenger and freight trains, multiple unit trains, and shunting engines. Of all locomotives operated by British Railways in 1958, less than 7 per cent were diesel, and of these some 93 per cent were shunting engines. About 70 per cent of diesel engine hours in traffic were for shunting purposes. Diesel engines other than those in shunting engines are fitted to multiple unit stock, and as mentioned in the paper are truck engines or, as I would call them, bus engines. These trains are two- or three-car units and operate over lightly loaded branch lines, mainly in rural districts. The electric traction referred to in the section of the report from which Table IX is derived is predominantly multiple unit stock operated by the Southern Region of British Railways and to a much smaller extent at present by the Eastern Region. These trains are six- or seven-car units carrying heavy suburban passenger traffic. The relatively few electric locomotives are those on the Manchester–Sheffield–Wath line and are used for hauling heavy freight traffic. It will be appreciated from what I have said that energy consumption for electric traction must inevitably be much greater than for diesel traction under the respective conditions of operation. Strictly comparable figures for electric and diesel traction operating under like conditions are not at present available, but I am assured that they will present a very different picture from that given in Table IX. I should perhaps add that the additional facts which I have just given are also derived from the 1958 Report of the British Transport Commission, though I will freely admit that I am indebted to a colleague on the staff of the Commission for help in finding them.

My next point, and here I am on more familiar ground, relates to the use of diesel in place of petrol engines in public service vehicles and goods vehicles. It is true that, so far as buses and heavy goods vehicles are concerned, the change was made on the basis of vastly improved fuel consumption, but as the diesel engine has developed, so has its robustness increased, and the mileage being obtained between overhauls is something that was undreamed of when the vehicles were using petrol engines. The author's remarks that " the working life of the (diesel) engine tends to be greater " is, in my experience, a considerable understatement. Like the author I too have wondered why diesel engines have made little or no headway in the U.K. for business cars. The position is, I think, somewhat different on the Continent of Europe. A possible explanation, apart from " amenity value," may be that many business concerns make a practice of replacing their cars on an annual basis. It seems likely that a diesel-engined car would have an appreciably lower secondhand value than a petrol-driven car of equivalent mileage. It may also be questioned whether diesel-engined cars would be operated and maintained so as to avoid emission of objectionable exhaust smoke. Many goods vehicle operators seem to find it difficult to do so. Experience with buses shows that there is no real difficulty, though carefully planned maintenance and constant vigilance are necessary.

Here, of course, the author may reply that the operators' problem would be eased by accepting a fuel of lower specific gravity and higher volatility. My own experience is that a small change, from a specific gravity of, say, 0·850 to 0·825, makes no discernible difference. A more drastic change might perhaps do so, but if it merely resulted in changing a dark grey smoke into one of light grey or whitish hue, no one would be much better off, and complaints would persist. In any case, operators of diesel-engined vehicles are strongly opposed to a fuel of lower specific gravity because of its adverse effect on fuel consumption, and even if by some magical alteration in price structure in the oil industry it became possible to offer a lower specific gravity fuel at a lower price, it is inconceivable that the margin could be sufficiently large as to leave total fuel costs, *i.e.* basic cost plus tax, unchanged. It would seem that such a situation could only be brought about were the fuel both purchased and taxed on the basis of calorific value, *i.e.* on a weight and not a volume basis. I must confess that the difficulties in making such a change, which would have to apply to all users, seem insuperable.

The author's reference to fuel cells is interesting and development has been exceedingly slow. I can recall it being stated at the British Association meeting held in Birmingham in 1950 that if one-tenth of the effort put into the development of atomic energy at that time had been devoted to the fuel cell, all problems would have been solved. Of the two types of cell mentioned by the author, the carbonaceous fuel cell, using, say, hydrocarbon gases or kerosine vapour, with atmospheric air as oxidant, is the more attractive to users of petroleum fuels, and its development will be closely followed. Although both energy efficiency and thermal efficiency are attractively high, much will depend upon the volume and weight of the multi-cell unit and ancillary equipment when the final stage of development is reached.

W. S. Ault: On the question of private transport, if we had not had any oil, I can only say that there would have been a lot more money available for developing electric batteries, and we might all be running about in more exciting versions of the electric broughams, of which there are one or two still around in London. That is the only

solution I can think of immediately. I cannot believe that we would have generated enough alcohol, both for transport and for human consumption, to use it as an alternative fuel.

On Table IX, I think the best answer is that I had better consult Mr Wilford and his colleagues. My recollection is that the heading as shown in the preprint is the heading as shown in the Report, but I must check that again.

Those figures have been quoted in that form in the press, and I will check back with those again, but there is no intention of producing misleading figures, because the point I was really trying to make was the very worthwhile savings of either diesel or electric traction in the widest senses, as compared with steam loco or trains and, of course, steam shunting, for which much more spectacular figures are still to be produced. The figure of 70 per cent of diesel usage was for shunting. That does not surprise me at all. I hope we shall see, not that percentage dropping in itself, but being swamped by increasing main line diesel haulage.

With regard to engine life I think I would agree with what Mr Wilford says. Our own experience with bus and truck operators who use the larger size of diesel comparable with those used by the LTE, is that lives of 2000 miles before overhaul are by no means uncommon to-day, and some operators get even more. Certainly some petrol engines do run that sort of mileage before overhaul in their larger sizes, but there we are not really comparing like with like; we are comparing a typical car petrol engine of 1½ to 2 litres with a diesel of about 9 litres, and their duties and standards of construction, and their prices per horsepower, are rather different. But certainly, if things are moving, they are moving in the direction that Mr Wilford quotes, of even better showing for diesel on life.

On the secondhand value of diesel cars, I should have thought that if it is worth buying a diesel car new, it is equally worth buying it secondhand, and that it would have adjusted itself. I think the answer is amenity value, and in amenity value I would include flexibility under our very crowded road conditions. The diesel cars I have driven myself, once they have been run up to about 65 to 70 miles an hour, go along very happily, but they take rather a long time to reach that speed. In France and Germany one can hold those speeds for mile after mile, but in the U.K. it is very rarely possible.

On volatility *v.* exhaust smoke, I would agree that increasing the volatility does help exhaust smoke, but in our experience it does not help it all that much, and I think that further study is required by engine designers, operators, and the petroleum industry. I would put in a plea that engines might be more conservatively rated. It is certainly the policy of the LTE to de-rate its engines quite substantially, and exhaust conditions are very good in consequence, on the whole. But I think other users and designers might be more conservative in choosing engines for a given duty.

The question of specific gravity *v.* cost is difficult. I would have thought that if there were, which as I say is unlikely, a very sweeping conversion from the spark ignition cycle to the diesel cycle, the disturbance created to the oil industry's price structure would be so severe that there would be a complete re-assessment of prices, and this new fuel would find an appropriate market level after demand had been met for some time.

R. Priddle: Historically, the growth of petroleum fuels consumption in many countries has been underpinned by the strength of demand in transport. In many areas the increase in this demand is slowing and, to a large extent, the main growth of consumption is now taking place in burning uses. Can Mr Ault envisage the emergence of new transport applications for petroleum fuels in the future? I have in mind something like the Hovercraft. Is this machine just a crank idea?

Secondly, what future does he envisage for liquid petroleum gases in transport uses?

Thirdly, can he see any resurgence, in the fairly distant future, of coal demand in railway applications via some form of gas turbine using pulverized coal? I believe this is being experimented on in the U.S.A. and also in Britain.

W. S. Ault: I think that the Hovercraft and devices of that type are basically quite sound. It might be very useful to the petroleum industry for exploration work in difficult terrain—a sort of super marsh buggy, in point of fact, and probably less troublesome. However, the increase in transport itself depends primarily on the economic development of any country—how much money people have to spend in getting from A to B and whether they need to get from A to B or not? And the higher the standard of living, the more often they want to get from A to B, just for the fun of it. So I cannot see that any new device, short of perhaps a very cheap helicopter, which anybody can drive, would make people travel very much more than at present by more conventional forms of transport.

Another possible development is a cheapened version of the Fairey Rotodyne, which is an impressive performer and is also very expensive at present. If it could be reduced in price it might become quite an attractive proposition for high grade freight transport, as well as high grade passenger transport.

Liquid petroleum gas is used in Europe—in Holland under rather special conditions for running buses. To make it competitive with other fuels, it has to be sold at a price per gallon substantially below the price of diesel fuel. The specific gravity is much lower, as you will appreciate, and therefore the heat energy per gallon is very much lower, but where, for any particular reason, liquid gas is available at a very low price, almost at distress price, and there is a demand for purely local transport (vehicles going not more than a few miles from base) it is quite an attractive fuel. It gives a very good engine life, is quite easy to handle, and is technically entirely satisfactory.

With regard to coal-burning gas turbines, I do not doubt they can be made to work, but I am not aware of one which is actually working as a turbine so far. It seems to me a very difficult task. Metering the coal is not so bad if it is pulverized, but getting rid of the ash is a very nasty problem. But we must just wait and see how the development programmes of the Ministry of Supply and one private firm get on.

B. R. Cutter: Mr Ault mentioned the failure of the railways to convert coal-burning locomotives to oil-firing. It seems to me that as this has been so successfully done on the marine side, the failure of the railways to do this has been less dictated by economic or even technical reasons, but more by the historic link which exists between the railways and the coal industry.

Is there anything that the author thinks can be done, in a short term, to remedy this, having regard to the fact that there are still quite a number of coal-burning locos in the U.K., and will be for some 20 years to come?

W. S. Ault: That is a question which is obviously fraught with politics. However, dealing with the technical side of it, it is not a very attractive proposition, on

technical economics, to convert a coal-burning steam loco to oil, because the oil fuel is more expensive, and by that conversion one does substantially increase the efficiency of the loco. There are several technical problems: one is that the fire box is the wrong shape, generally; another is that one wants to fire it from the wrong end; a third is that the coal-fired steam loco is very largely self-adjusting. If you visualize a nice bed of fuel built up in the fire box, and the driver is going up a gradient, and he opens the throttle more, if it is not already full open, and he alters the regulator setting, which admits more steam to the cylinders, there is more exhaust steam coming out of the blast pipe, there is a greater draught, and the coal is automatically burnt. That does not apply with oil fuel. If a loco is converted to oil fuel one has to put on quite elaborate regulating devices to adjust the rate of firing to the rate of steam demand, and a loco boiler has not a great deal of reserve. One must fire it or burn the fuel at a rate pretty close to the rate of steam demand, or one will run into trouble.

Summing up briefly, coal is more or less foolproof and self-adjusting, while oil is rather difficult to control.

E. Atkinson: A short time ago I think we would have had several keen followers of the gas turbine on their feet, to suggest reasons why that machine could be used by the railways. As it is, of course, if one introduces something new one must just not achieve parity with an existing machine; to make it commercially acceptable, one should be able to offer a substantial advantage. If the gas turbine at present operating is considered there are many reasons why it is not equal to the diesel engine. Now, it has everything in its favour—by that I mean the current design has everything in its favour; it is handling a liquid fuel, but, of course, the load condition varies, and results are affected by combustion efficiency, which varies with the load. If one considers a turbine burning a solid fuel, it will be appreciated that there will be considerable difficulties, and that the problem is very much greater than the unit burning a liquid fuel. It is true that a solid-fuelled gas turbine unit was developed—at least it went through some development stages—and possibly by now it may be developed further because of pressure from the National Coal Board, but that is outside the scope of this meeting. Considerable experimental work would be necessary, I am sure, to prove a case for such a machine.

The meeting then closed with a warm vote of thanks to the author.

REFINING OF LUBRICATING OILS BY CHROMATOGRAPHY *

By GYULA NYUL † and ENDRE VAMOS †

INTRODUCTION

Among the industrial methods generally used in the refining of lubricating oils, solvent extraction is the most up-to-date process. However, it is a fundamental disadvantage of this method that the separation of lubricating oil components will not be complete due to mutual solubility relations. Any refining principle resulting in sharper separation would therefore mean a considerable improvement.

The objective in lubricating oil refining practice is, in the first place, the sharpest possible separation of saturated hydrocarbons. This group of compounds comprises, besides *iso*-paraffins, mainly *cyclo*-paraffins with side chains (so-called naphthenes). Apart from these, lubricating oil distillates also contain considerable amounts of components having an aromatic character, *i.e.* aromatic compounds with side chains. The effect of non-condensed aromatic compounds with long side chains in the oils is still under controversy,[16] while condensed ring aromatics are decidedly detrimental. Further important components are the so-called resinous constituents, which are characterized by condensed ring systems and short side chains, as well as the presence of molecules containing sulphur and oxygen, possibly also nitrogen. Highly condensed components of largest molecules, containing also S, O, and N and mostly possessing colloidal structures, are called asphaltic constituents. The latter are of considerable importance only in residues, and practically do not occur in distillates.

The above-mentioned groups of compounds are of increasingly polar character, corresponding to the above sequence. Their adsorbability on polar adsorbents increases therefore in the same order. Attempts have long been made to utilize this phenomenon in the refining of petroleum products.[4, 5] This is fully justified, since chromatographic separation proved to be more advantageous even in first approximation than, for example, solvent extraction. As an illustration, a series of refining experiments will be disclosed, carried out on dewaxed motor oil distillate from Lispe, Hungary, on the one hand with cresol, and on the other by chromatographing with Fuller's earth or silica gel. Under optimum conditions, different qualities and quantities of raffinates were obtained in the solvent extraction experiments by varying the oil/solvent ratio. The same oil was chromatographed from pentane solution on silica gel and Fuller's earth columns respectively, and the different raffinates were obtained by changing elutrient (dichloroethane) quantities. The viscosity indexes of the raffinates produced are shown in Fig 1, as functions of the corresponding yields. Adsorption refining resulted in considerably higher qualities with identical yields, and in higher yields with identical qualities.

It is therefore clear why an ever-increasing interest has recently been shown in adsorption and chromatographic processes. A great deal of work has been done on the separation of petroleum products by cyclic chromatography. Among them, methods for the separation of light hydrocarbons have also been realized on a commercial scale.[2, 3, 6, 7, 10, 13–15, 20, 22, 28] From a practical viewpoint, however, many questions will have to be answered in connexion with methods for refining of lubricating oils, and there still exists considerable necessity for further development.[1, 9, 11, 12, 16, 17, 23, 24, 26, 27]

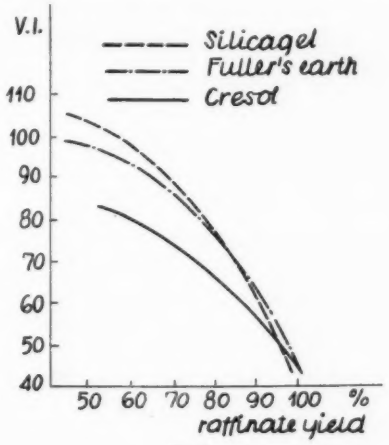

Fig 1

COMPARISON OF SOLVENT EXTRACTION AND ADSORPTION REFINING

Obviously it is of the first importance that a given quantity of adsorbent may be utilized for the refining of the largest possible quantities of substances. This is, however, limited by the fact that the adsorbent will be saturated upon adsorption of a certain quantity (10–30 per cent), *i.e.* its further utilization is rendered possible only by inserting regeneration operations. It

* MS received 30 November 1959.

† Hungarian Petroleum and Gas Research Institute, Budapest.

is advisable to regenerate the adsorbent by a suitable elutrient. The processes envisaged by the authors of the present paper were refining procedures on a fixed bed in cyclic operation. According to this, the following steps were established. (1) The lubricating oil in question is dissolved in an adequate solvent and passed through a column packed with adsorbent, whereby the polar constituents are retained by the adsorbent. Upon passing a certain quantity through the column, it will be saturated and most of the raffinate will then be present in the liquid phase, *i.e.* in the interstices of the adsorbent particles. (2) Upon saturation, passing of the solution to be refined is stopped and the column washed by pure solvent to remove the raffinate solution from the interstices. (3) Upon solvent washing, the polar constituents, the so-called extract materials, must be removed by a suitable solvent, *i.e.* the elutrient. (4) After removal of the extract materials, the column saturated with the elutrient must be washed with the original solvent, following which it may again be used for refining further charges.

Taking into account the above, the following questions had to be dealt with:

1. Selection of the adsorbent.
2. Selection of the solvent.
3. Regeneration of the adsorbent.

1. *Selection of the Adsorbent*

It is known that polar adsorbents are suitable for separation of mineral oil constituents. Of these, the adsorbent with the highest selective adsorption capacity and which may easily be regenerated will obviously meet the purpose best. In order to select the most satisfactory material, runs were carried out on spindle oil and motor oil distillates, employing various adsorbents. Identical quantities of the suitably diluted distillates were carried on the adsorbent column and the raffinate was washed from the column with identical solvent quantities, whereupon the spindle oil and the motor oil were extracted with dichloroethane and acetone respectively. The regeneration capacity was described by the relative quantities of the constituents which cannot be eluted with dichloroethane or acetone. A silica gel marked " sterling gel " was taken as a standard sample (see Table I). The relative quantities (Q) have been expressed in terms of

$$Q = \frac{\text{Wt \% unelutable from adsorbent studied}}{\text{Wt \% unelutable from sterling gel}}$$

It can be seen from the data in the table that with spindle oil the silica gel and the polar activated carbon proved most suitable, whereas with motor oil having higher molecular weights the silica gel was found satisfactory.

It was confirmed by further investigations on the selection of silica gel type that the pore diameter of the silica gel should permit diffusion at suitable rate of the molecules to be adsorbed, and the adsorbent should at the same time have as large an active surface as possible, for the sake of adsorption capacity.

TABLE I

Experiments on Selection of Adsorbent

Adsorbent	Spindle oil: ratio of part not elutable by dichloroethane	Motor oil: ratio of part not elutable with acetone
Bauxite	3·6	50–75
Charcoal	*	*
Activated carbon	1·6	†
Fuller's earth	5·6	20
Aluminium hydrate gel	2·6	—
Silica gel (sterling gel brand)	1·0	1
Activated alumina	8·5	200–225

* The adsorbent is poorly wetted by the solution.
† Refining effect is incomplete.

According to the experiments, a silica gel with a pore radius of about 25 Å and with an approximate specific surface of 600 sq m/g proved satisfactory for the refining of spindle oil.

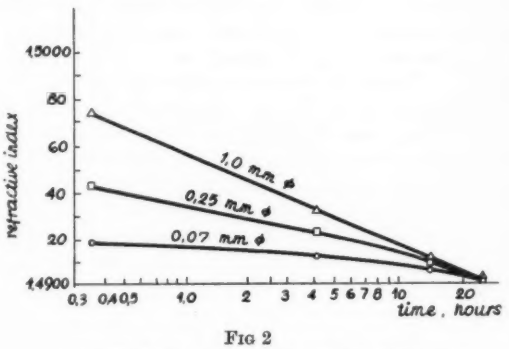

FIG 2

EFFECT OF PARTICLE SIZE ON THE PROCESS

It is advisable to select the smallest possible particle sizes, since the diffusion time within the particles represents a very important factor determining the rate of the process. Evidently size reduction decreases the length of diffusion time and thus increases the rate of the process. This is proved by Fig 2, representing the change of the refractive index in a 10 per cent solution of spindle oil in pentane as a function of time, when adsorbed on silica gels of different particle sizes. It can be seen that the adsorption equilibrium is approachable in much shorter time with small particle sizes. Size reduction is, however, limited by the fact that passing the solutions through fine adsorbent particles at identical rates can only be brought about under pressure. A compromise is therefore necessary, which permits operation under moderate pressure, with flow rates satisfactory from a

practical viewpoint. In the case of spindle oil refining, accounting for a pressure drop of 20 atm, particle sizes of 50–150 μ proved adequate. The correlation between pressure drop and particle size was calculated according to a method described in the literature.[21]

2. *Selection of Solvent*

The viscosity of the feedstock must be decreased by addition of solvent in order to accelerate its passing through the adsorbent. Apart from the decrease of viscosity, the solvent must be selected so as to allow for maximum adsorption from the solution of the constituents to be separated, *i.e.* the solvent proper should be adsorbed to a small extent. For this purpose, adsorption experiments were carried out on a chosen standard hydrocarbon (α-methylnaphthalene) from different solvents. The selection of the above hydrocarbon as standard is justified by Fig 3, according to which the isotherm of the extract materials obtained by chromatography from spindle oil and measured in

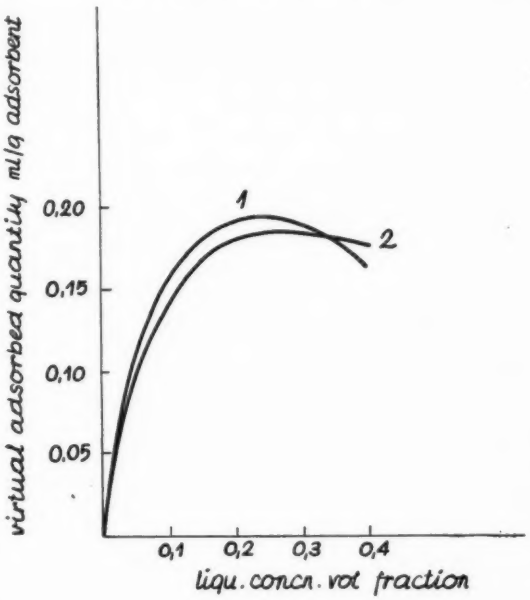

FIG 3

ADSORPTION ISOTHERMS OF α-METHYLNAPHTHALENE AND SPINDLE OIL EXTRACT IN CETANE SOLUTION

n-cetane solution was found to be close to that of *n*-cetane-α-methylnaphthalene.

The isotherms of α-methylnaphthalene are shown in Fig 4. Non-polar solvents, *e.g.* carbon tetrachloride and saturated hydrocarbons, meet the purpose best. Selection from among the above-mentioned solvents could be carried out on a merely practical basis. Carbon tetrachloride seemed to be less satisfactory, due to possible decomposition and higher costs. Among the saturated hydrocarbons, the higher molecular weight types show better adsorption properties, but are disadvantageous on account of their lower volatility and higher viscosity. Technical pentane showed outstanding advantages in practical chromatographic experiments, because of its higher volatility, low viscosity, and low cost. The isotherm of pentane has not been taken due to experimental difficulties; moreover, this step has not been considered necessary

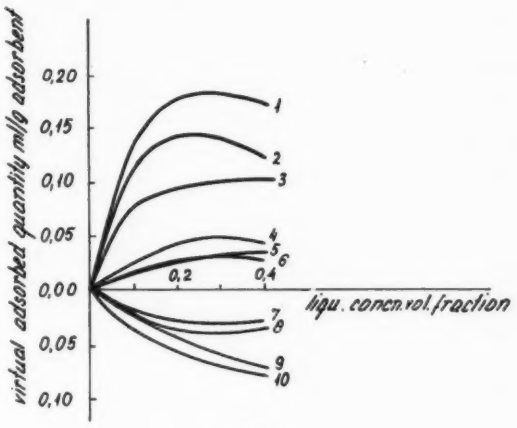

FIG 4

ADSORPTION ISOTHERMS OF α-METHYLNAPHTHALENE IN VARIOUS SOLVENTS

1. *n*-Cetane
2. *n*-Heptane
3. Carbon tetrachloride
4. *o*-*m*-*p*-Xylene
5. *p*-Cymene
6. Toluene
7. Benzene
8. Dichloroethane
9. Diethyl ether
10. Acetone

because of small differences in molecular structure and molecular weight, as compared with heptane.

The solvent is further used to remove the polar elutrient remaining on the column after the elution step. The removal of the elutrient from the interstices of the adsorbent, as well as the adsorbed phase by the non-polar solvent, which is used in relatively much larger quantities, is due to changes in concentration relations. Owing to fundamental reasons, no quantitative effect may be obtained in this phase with the solvent. The process has, however, proved entirely satisfactory, with a suitable elutrient, for the purpose of obtaining, in a series of cyclic operations, raffinates of identical quality in practically identical quantities on the column regenerated with it.

3. *Regeneration of the Adsorbent*

Regeneration of the adsorbent consists mainly in the removal of the so-called extract materials to the greatest possible extent. For this purpose, those elutrients seem to be suitable in first approximation, which are more polar than the constituents to be removed by adsorption. Numerically, the polarity

has been characterized by the heats of wetting as per unit active surface of the adsorbents.

The polarities of the components of the feedstocks in question, characterized by the heats of wetting of the constituents separated by chromatography, are given in Table II. Sharpest possible separation of

TABLE II

Specific Heats of Wetting of Petroleum Distillates on Silica Gel

	Heat of wetting, Q, cal/sq m
Spindle oil:	
Saturated part	0·018–0·019
Aromatic part	0·035–0·038
Resinous part	0·042–0·045
Motor oil:	
Saturated part	0·020–0·023
Aromatic part	0·040–0·043
Resinous part	0·045–0·048

the constituents involved feeding the pentane solution of the feedstock on the chromatographic column; washing with pentane until the refractive index reaches a minimum (saturated part); further elution with benzene until the refractive index of pure benzene was reached (aromatic part); removal of the so-called resinous constituents, retained on the column, by chloroform–acetone mixture. The heats of wetting of the products obtained were measured in heptane solutions of different concentrations. Since the correlation proved linear, the heats of wetting of the pure constituents were extrapolated. The polarities of the different solvents were characterized in a similar way, as per the data compiled in Table III.

TABLE III

Specific Heats of Wetting of Solvents on Silica Gel

	Heat of wetting, Q, cal/sq m
Carbon tetrachloride	0·014
Technical pentane	0·014–0·016
Carbon disulphide	~0·016
Normal heptane	0·016
Aromatic-free gasoline	0·015–0·017
Technical xylene	0·025
Toluene	0·032
α-Methylnaphthalene	0·035
Benzene	0·039
Diethylether	~0·040
Thiophenol	0·042
Thiophene	0·042
Dichloroethane	0·043
Acetone	0·047
Ethanol	0·053
Methanol	0·054

Comparing the data of the two tables, it can be stated that the best elutrients proved to be the ones of which the polarities exceed that of the constituent having the highest adsorbability, *i.e.* of the resinous components, which amounts to 0·045 and 0·048 for spindle oil and motor oil, respectively. The experimental data listed in Table IV confirm this statement completely.

TABLE IV

Elution Experiments with Various Solvents on Silica Gel at 20° C

Elutrient	Heat of wetting, cal/sq m	Non-eluted material as per feed oil quantity, %
Acetone	0·047	0
Dichloroethane	0·043	0·5
Diethylether	~0·040	4·8
Benzene	0·039	5·0
Carbon disulphide	~0·016	7·33
Pentane	0·014	15·0

From a practical viewpoint, however, the elutrient to be selected must in turn be removed completely and economically by the original non-polar solvent after total removal of the extract materials. This, however, would require less polar elutrients, which is contrary to the previous requirements. The necessity for a compromise arises, which is quite feasible, since elutrients of relatively smaller polarities may be suitable for the removal of extract materials, when increasing the quantity per cycle of the elutrient. Taking into account both viewpoints, an elutrient of closely similar polarity to that of the most polar constituent to be removed had to be selected.

On the basis of the above considerations, use of dichloroethane as elutrient in spindle oil refining seems to be advisable, whereas with motor oils only the aromatic constituents will be removed by this solvent. The latter can therefore be employed only with starting materials previously freed from resinous constituents by propane raffination. In order to avoid these difficulties, two alternative methods have been developed, namely:

(*a*) The adsorption step is divided into two operations. Only the resinous constituents are first adsorbed and from the solution free from resinous constituents the raffinate proper will be separated on a second column. In correspondence with this, the first column must be regenerated with an elutrient of higher polarity, and the second column with an elutrient possessing lower polarity. In the experiments, acetone and dichloroethane or benzene were found satisfactory for this purpose.

(*b*) The effects of some elutrients on elution efficiency were investigated as a function of temperature. Certain characteristic experimental data are shown in Fig 5. It can be gathered from these that the eluting activity of the solvents in question increases with temperature. This may be explained by the fact that the adsorption capacity of the adsorbent towards both extract materials and solvents decreases as the temperature increases. On the basis of this, a procedure

has been developed, in which aromatics may be eluted with cold benzene, whereas the adsorbed resinous constituents may be removed with hot benzene.[19]

According to the viewpoints disclosed above, three procedures were developed, corresponding to the process described, which differ only in the method of adsorption adapted to the stock to be refined, and that of desorption as required by the adsorbed material.

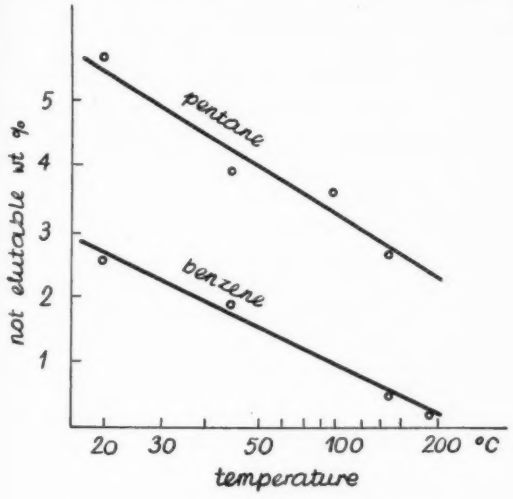

FIG 5

EFFECT OF TEMPERATURE ON THE ELUTION

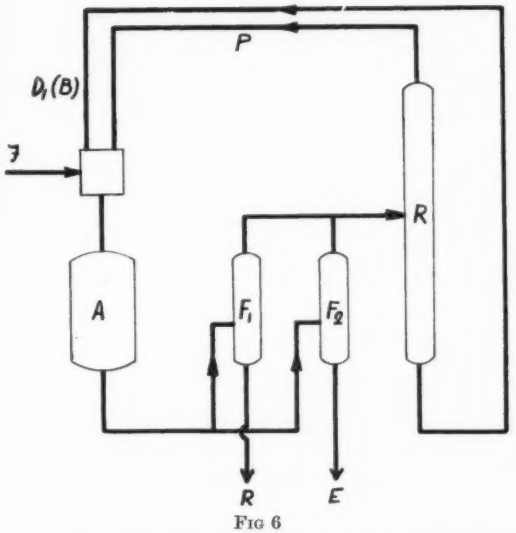

FIG 6

SCHEMATIC DIAGRAM OF ONE-STAGE ELUTION PROCESS

I—Input
D—Dichloroethane
B—Benzene
P—Pentane

(i) *One-stage elution*

The realization of the cyclic chromatographic principle depends to the greatest extent on the problem as to whether the adsorbent column can be regenerated economically. This in turn requires that the polar elutrient, retained on the column upon desorption, could be removed by the smallest quantities possible of the original diluting solvent. This condition may best be accomplished by using an elutrient of middle polarity. Again, this can be done only if the extract materials to be eluted are not very polar either. This requirement is met, in the first place, by light oil distillates, as well as residual oils previously de-asphalted and de-resined with propane. For a flow sheet of the process see Fig 6.

The starting stock, dissolved in pentane, is fed to the adsorber, A. Upon feeding the quantity necessary for saturation of the adsorber, the raffinate solution is removed by pure pentane. The solution is freed from solvent in the flash column F_1. The raffinate is obtained as a bottom product of the column. Suitable quantities of dichloroethane are then passed through the adsorber and the rest of the dichloroethane removed by pentane wash. The solution is freed from solvent in column F_2, the bottom products of which are the extract materials. The solvent and elutrient distillates, which are contaminated with each other, will be rectified in column R, and the pure products returned into the cycle.

TABLE V

Refining of Paraffin-Free Machine Oil Distillate by One-Stage Elution

	Feedstock	Raffinate	Extract
Yield, wt %	100	53	47
Density, d_4^{20}	0·918	0·892	0·946
Refractive index, n_D^{20}	1·5070	1·4898	1·5281
Molecular weight	381	388	352
Viscosity, cS/100° F	99·83	68·68	160·56
Viscosity, cS/210° F	8·82	7·67	10·38
Viscosity index	54	78	16
Flash point, Marc °C	224	240	224
Pour point, °C	−27	−36	−27
Conradson residue, wt %	0·13	0·02	0·35
Acid number, mg KOH/g	0·09	0·00	0·06
Iodine number, Winkler	17·4	6·1	24·7
Extinction, Pulfrich, filter 9	3·1	0·12	16·0
Sulphur, wt %	0·17	0·04	0·27
C_A, %	15·2	6·6	27·1
C_N, %	36·5	39·5	30·5
C_P, %	48·3	53·9	42·4

The process described above has been tested also in a pilot plant. A quantity of 2 bd of spindle oil distillate was processed to white oil of the quality and with the yield predicted in laboratory experiments. The process is suitable for refining of residual oil previously dewaxed and freed from resins with propane. Experimental data on machine oils are listed in Table V.

(ii) *Two-stage refining*

The method described above is not suitable for chromatographic refining of high viscosity lubricating oil distillates or of propane raffinates not de-resined, since the adsorbed material to be eluted contains components of high polarities, *i.e.* of strong adsorbabilities, which cannot be removed by the solvent of middle polarity used without adverse economics involved. This, however, may be accomplished by bringing about adsorption in two subsequent columns,

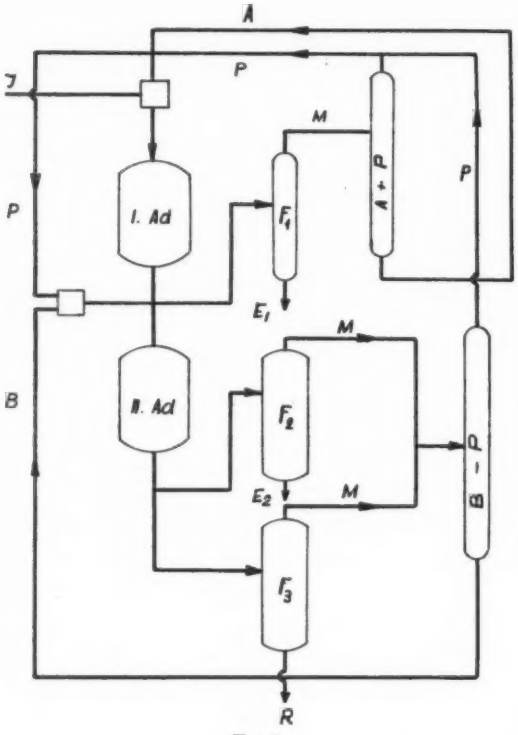

FIG 7

SCHEMATIC DIAGRAM OF TWO-STAGE ELUTION PROCESS

I—Input
P—Pentane
B—Benzene
M—Mixture
A—Acetone

the first of which retains the so-called contaminants of highest polarity, whereas on the second column the less polar extract materials are adsorbed. The individual columns must, of course, be regenerated separately, utilizing a high polarity elutrient, *e.g.* acetone, for the first column, and eluting the second column with a solvent of middle polarity, such as dichloroethane or benzene. The flow sheet of the process is shown in Fig 7.

Passing the starting stock dissolved in pentane through adsorber, I Ad, a semi-raffinate is obtained, which is further treated in adsorber II Ad. Upon saturation, adsorbers I Ad and II Ad are eluted with acetone and dichloroethane or benzene, respectively. By removing the solvents from the products in the corresponding flash columns F_1, F_2, and F_3, raffinate R and extracts E_1 and E_2 are obtained. The solvents, contaminated with each other, are separated in rectification columns $A + P$ and $B + P$ and returned into the cycle.

The data listed in Table VI shows the properties of the feedstock as well as the raffinates and extracts obtained on refining a motor oil distillate by the above two-stage procedure. In comparison, data for a closely identical product obtained by refining with furfural are also given. Chromatographic refining resulted in yields 10 per cent higher than those given by furfural refining.

(iii) *Elution with hot solvent*

It has been mentioned that elution efficiencies may also be increased by employing hot elutrients. Increase of temperature has the same effect as if the polarity of the elutrient were raised. The importance of this phenomenon lies in the fact that solvents of middle polarity may also be used for the removal of strongly polar extract materials. A similar effect was made use of by Eagle and Scott, when employing a hot paraffinic solvent in the chromatographic separation of light hydrocarbons.[6, 7] When refining heavier distillates also containing resinous constituents, the paraffinic solvent cannot exert adequate eluting effect. According to the experiments, however, a hot aromatic elutrient, such as benzene, permits repetition of the chromatographic cycle also in such cases. This seems to be advantageous, because the materials to be adsorbed, although possessing polarities of a wide range, may be eluted with a single solvent. Applying this principle, the process becomes more adaptable, since the same elutrients can remove aromatic constituents when cold, while in a hot state resinous constituents will also be eluted. Direct application of a hot elutrient removes, of course, all the extract materials.

TABLE VI

Refining of Motor Oil by Two-Stage Elution

	Feedstock	Semi-raffinate	Raffinate	Extract I	Extract II	Furfural raffinate *
Density, d_4^{20}	0·936	0·925	0·906	1·038	1·007	0·902
Flash point, °C	238	240	239	—	—	245
Viscosity, cS/100° F	361·3	238·1	144·7	—	—	175·6
Viscosity, cS/210° F	17·8	14·5	11·8	—	—	11·2
Viscosity, SUV/210° F	88·9	75·8	65·7	—	—	71·2
Viscosity index	35	46	71	—	—	70
Conradson residue	1·2	—	0·2	—	—	0·2
Refractive index	1·5192	1·5149	1·4966	1·6658	1·5650	—
Pour point	−17	—	−15	—	—	−16
Yield, wt %, direct †	100	89	77	—	23	—
Yield as per feedstock	—	—	69	11	20	63

* Soft bituminous material, R & B softening point 28° C, ductility at 15° C 1000 mm.
† Calculated on feedstock of the individual operation.

The procedure is carried out according to the schematic diagram shown in Fig 6, with the difference that heating and cooling of the elutrient and the adsorption system must be provided for. In the laboratory experiments the feedstock disclosed in Table VI was refined, and the quality and yield data proved identical, both for the raffinates and extract materials, with those obtained in the process operated with two elutrients.

In Table VII results of the refining of a heavy motor oil distillate are given. An attempt has also been made to show the effect on chemical composition. The more paraffinic character of the raffinate as compared with the feedstock can even be established by density, refractive index, and viscosity index data. As regards results of elemental analysis, the same premise is confirmed by the increased hydrogen content, whereas the decrease in sulphur content shows that the process is suitable for efficient removal of sulphur compounds also. The above statements are also backed by the results of ring analysis.

TABLE VII

Refining of Heavy Motor Oil Distillate by Hot Elutrient Process

	Feed-stock	Raffinate	Aromatic extract	Resinous extract
Yield, wt %	—	52	30	18
Density, d_4^{20}	0·941	0·904	0·936	1·032
Refractive index, n_4^{20}	1·5210	1·4965	1·5198	—
Viscosity, cS/100° F	475·3	167·3	326·6	—
Viscosity, cS/210° F	19·4	13·3	16·0	—
Viscosity index	16	76	22	—
Conradson residue %	1·6	0·1	0·6	5·5
Iodine number, Winkler	48	17	55	115
C %	86·6	86·2	86·9	87·4
H %	11·8	13·2	12·4	9·7
S %	0·3	0·1	0·3	0·7
O (+ N) % (difference)	1·3	0·5	0·4	2·2
Molecular weight	426	447	395	403
Average composition, $C_xH_yO_vS_z$				
x	31	32	29	29
y	50	59	49	39
v	0·35	0·12	0·10	0·58
z	0·04	0·02	0·03	0·09
C_A % in aromatic linkage	17·0	7·0	17·2	39·1
C_N % in naphthenic linkage	37·2	40·1	40·0	42·2
C_P % in paraffinic linkage	45·8	52·9	42·8	18·7
R_A aromatic rings per mole	0·5	0·4	0·8	2·0
R_N naphthenic rings per mole	3·1	3·0	2·8	3·5

Evaluation Viewpoints

The processes described have several outstanding advantages as against other lubricating oil refining methods. Among these, the most important features are sharper selectivity, *i.e.* resulting in higher yields, also the possibility of elimination of sulphuric acid together with acid sludge as compared with some other procedures.

The one-stage elution chromatographic process applied to the production of instrument lubricants has been compared in Table VIII with the conventional sulphuric acid refining. It can be gathered from this that raw material and chemicals requirement for one ton of finished product is very much smaller in the case of adsorption refining. With acid refining, the whole amount of by-product is practically detrimental waste (acid sludge), whereas that of the adsorption process is a useful lubricant (see the quality shown in the extract column of Table V).

However, the disadvantages of the cyclic chromatographic processes present themselves in the costs of solvent distillation. The solvent requirements of the processes described are shown in Table IX. From the viewpoint of so-called white oils, where the costs of acid refining are very high, the economy of the processes is not impaired. When, however, heavy lubricating oils are to be refined, the solvent requirements seem to be rather high, if the refining operations are considered as a separate process.

TABLE VIII

Production of Instrument Oil (Yellow Vaseline Oil)

Data calculated for 1000 kg product	Acid refining, kg	One-stage chromato-graphic refining, kg
I. *Raw material and chemicals*		
Spindle oil	1820	1250
H_2SO_4 + oleum	730	—
Loss of alcohol	36	—
Loss of solvent	—	6
II. *Products and wastes*		
Instrument oil	1000	1000
Machine oil	—	250
Naphthenic acid soaps	10	—
Acid sludge	1540	—

TABLE IX

Average Solvent Requirements

Solvent requirements in wt % of raffinate	Chromatographic method		
	One-stage	Two-stage	Hot solvent
C_5–C_6	500	500	500
Benzene	—	200	300
Dichloroethane	300	—	—
Acetone	—	300	—
Total	800	1000	800

The situation is considerably improved if the adsorption process is integrated into the total process scheme, thus rendering it possible to carry out in the same solvent (propane) the de-asphalting, refining, and dewaxing. In Table X the solvent requirements of individual complex refining sequences are compared, calculated on the basis of the same quantity and quality of raffinates.

In one of the series of experiments upon propane de-asphalting, furfural refining and dewaxing in MEK–benzene solution were carried out, whereas in the other series, after deasphalting with propane the same stock was refined by adsorption method, from propane solution by one-stage elution process, which, in turn, was followed by dewaxing from the same solution. The difference in the solvent requirements between

the two series does not seem to be considerable, especially if the fact is taken into account that the distillation of solvents in the adsorption process is simpler and less expensive.

TABLE X

Comparison of Solvent Requirements

Solvent requirements in wt % of raffinate	Solvent refining	Adsorption one-stage
Propane de-asphalting	900	900
Solvent refining: furfural	250	—
Adsorption refining:		
Propane	—	400 *
Dichloroethane	—	300
Dewaxing:		
MEK–benzene	250	—
Propane	—	— †
Total	1400	1600

* Excess propane for column washing.
† Operation is carried out in the original propane solution.

The processes described are the results of extensive laboratory investigations of several years, which are substantiated by pilot-plant experiments also, the latter only carried out for lighter oils for the time being. It may be concluded from these results that the application of the principle of chromatographic refining of lubricating oils to commercial purposes may be adequate for light oil refining and may also be promising for heavier oils.

ACKNOWLEDGMENTS

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VARIATIONS WITH ELEVATION OF KUWAIT RESERVOIR FLUIDS *

By GEORGE HETHERINGTON † (Fellow) and A. J. HORAN † (Associate Fellow)

SUMMARY

In the Kuwait oilfields the density and other properties of the oil vary with elevation. This must be true of all oil bodies, and for that matter of bodies of any fluids, particularly those which are mixtures or solutions not subject to constant agitation. In smaller oilfields, with oil columns only a few feet thick, these changes may be insignificant, and have generally been overlooked. In Kuwait, with oil columns hundreds of feet in thickness, the variations are large and obvious. They are of profound significance in assessing the contents of the reservoirs, in determining their behaviour under production, and procedures which will be advantageous in their development.

Properties of the hydrocarbon fluids, whose variations have been investigated, are:

(1) The oil gravity.
(2) The gas gravity.
(3) The in-place, or solution, gas–oil ratio.

Together these are a description of the reservoir fluid composition.

(4) The density of the oil containing the dissolved gas in the reservoir.

This determines the pressure gradient in the oil, which varies with elevation.

(5) The saturation pressure.
(6) The compressibility of the reservoir fluid.
(7) The reservoir fluid viscosity.

All of these properties change comparatively slowly with elevation in the upper two-thirds of all the reservoirs. Towards the bottom, there is, in all cases, a rapid and increasing change to a heavy, tarry, and highly viscous fluid at the oil–water interface. This is sometimes referred to as a " tar mat." Relatively, the variation of the viscosity is far larger than that of the other properties.

The properties of the interstitial and bottom waters within the reservoir and its aquifer also vary with elevation. The interstitial water is all strong brine, but the quantity of dissolved solids is least at the tops of the reservoirs. The salinity and density of the interstitial water increase and its compressibility decreases with increasing depth. These changes continue into the water-bearing sand below and around the oil reservoir proper.

The variations described represent averages of the properties of individual fluid samples. When the properties as measured are plotted against sampling elevation, the scattering is considerable. This scattering is apparently related to extensive barriers to free fluid flow within the oil bodies; these barriers may be horizontal, shales or other impermeable layers following the bedding, or vertical, caused by faults and/or lenticularity in the sand.

INTRODUCTION

SINCE the hydrocarbons of oil and gas reservoirs are mixtures of large numbers of chemical compounds of varying density and exist in gravitational fields, their compositions and properties should vary from top to bottom. Variations in composition are detectable in even small masses of static liquid hydrocarbons. This has long been recognized, and tanks of crude oil are commonly sampled near the top, the middle, and the bottom to obtain a representative measure of the average quality of the oil. Accumulation of recoverable hydrocarbons are a consequence of gravity segregation in the permeable reservoir rock between gas, oil, and water. The gravitational force which produced this segregation should also produce segregation within the oil, gas, and water bodies as well as between them. Sage and Lacey [1] presented a theory for this segregation in 1939.

Nevertheless, the non-uniformity of reservoir oils has generally been overlooked or ignored in investigating the contents of oil reservoirs or in explaining and predicting their behaviour under production. In many cases the effects of this non-uniformity are probably insignificant in comparison with the other uncertainties as to the size, character, and probable behaviour of the reservoir. Only the more pronounced variations would be detected by analyses of separator liquids and gases as ordinarily performed. Elaborate and precise analyses of tank oils, as a guide to appropriate refinery processes, are fairly common. Without equally precise analyses of the gas and, what is most frequently missing, accurate measurement of the gas–oil ratio, such analyses are only semi-quantitive measures of the properties of the reservoir fluids, and the produced fluid is often not representative of the fluids in place.

Many thousands of oil and/or gas reservoirs in other parts of the world have been discovered and are being produced. For all but a small fraction, the only information ever collected on the properties of the reservoir fluid is the gravity and viscosity of a separator oil, and a rough approximation of the producing gas–oil ratio, which may not be representative of the in-place ratio. For many others, only one or, at most, two or three valid reservoir samples have been taken, and one of these or an average is assumed to represent the whole oil body. In Kuwait, however, extensive sampling and testing, even in the early development period, has been done, and as a result unusually complete information on the lack of homogeneity of the reservoir fluids was disclosed.

* MS received 8 October 1959.

† Kuwait Oil Co. Ltd.

Variations with elevation in the properties of reservoir oils have been described in considerable detail, and applied in reservoir analysis. As early as 1926, Eastbrook and Rader [2] noted the existence of a zone of " dead oil " near the bottom of the productive Well Creek sand, Salt Creek field, Wyoming. Burtchaell in 1949 [3] presented the results of a reservoir study in which variations with elevation in the properties of the oil were taken into account. Espach [4] in 1951 described in detail the variations with elevation in the properties of the oils in the Tensleep sandstones, Elk Basin field, Wyoming, and the Weber sandstones, Rangely field, Colorado. McCord,[5] in his study of the LL 370 reservoir, Lake Maracaibo, divided the reservoir into layers for his analysis, using oil gravities, solution ratios, saturation pressures, and oil viscosities changing progressively with elevation. Stewart *et al* [6] published in 1953 a study of reservoir behaviour in which the variations of hydrocarbon properties were allowed for, showing a notably close agreement between calculated and actual reservoir performance.

The variations of gravity and other properties with elevation within oil bodies should not be confused with another but related phenomenon. Among separate reservoirs, those at greater depth usually, but not always, contain lighter oils, with higher in-place gas–oil ratios and lower sulphur contents. This variation is opposite to that within any one oil body. Separate or semi-separate reservoirs frequently occur one above the other. The boundary may be obscure. If a separation does exist but is not recognized, observed data could be interpreted to indicate a decrease in density with increasing depth within an apparently continuous oil body.

THE SOUTH-EAST KUWAIT RESERVOIRS

The oil reservoirs of Kuwait, particularly those of the Burgan, Magwa, and Ahmadi fields, are conspicuous examples of segregation within oil bodies. The thick oil columns occur in a predominantly sandstone section, broken near the top by a persistent limestone, generally bordered above and below by shales, and continuous over the whole area. The comparatively thin sand section above the limestone has, in each field, been developed as one reservoir. This is called the Wara sand. The much thicker, lower sands have been developed as two reservoirs. These are known as the third and fourth sands, and together they constitute the Burgan formation.

The oil bodies in all parts of this section and in all parts of the South-east Kuwait fields are all bounded at the bottom by the same oil–water interface, which is almost, if not exactly, horizontal. Fig 1 is an idealized cross-section of the Main South-east Kuwait fields. The Magwa structure, off the line of the section, is shown behind Ahmadi. Wells so far drilled are mostly on the higher parts of the anticlines. The structure in the saddle between Burgan and generally around the flanks of the structure is inferential.

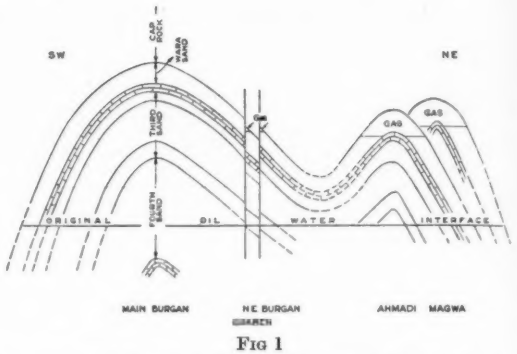

FIG 1

SOUTH-WEST NORTH-EAST SECTION, SOUTH-EAST KUWAIT FIELDS

FLUID DISTRIBUTION IN THE WARA SAND—BURGAN FIELD

Of the reservoirs of the South-east Kuwait fields the Wara sand of the main Burgan field has the longest oil column. The Wara consists of a number of sand members broken by shales. In the upper, or first sand, the sand members are mostly continuous over the top of the Burgan structure. In the lower part of the Wara, also known as the second or " Q " sand, there are thick sands around the flanks of the Burgan structure, but over the crest this section is predominantly impermeable shales. No original gas cap was found in the Wara sand at the top of the main Burgan structure. Gas caps, associated with faults, occur in the north-east part of the field. Much larger original gas caps were found in the Wara sand at the tops of the Magwa and Ahmadi structures.

In Fig 2 are shown the " stage " gravities of Wara sand oils plotted against the mid-points of the perforated intervals of the wells from which the samples were obtained. These " stage " gravities are the gravities of oils taken under pressure from the wellheads of flowing wells and weathered at atmospheric pressure after being reduced to a uniform low temperature. They rather roughly approximate in gravity flow-line oils from the field separators.

It will be noted on Fig 2 that while there is an obvious trend from heavy oils in the lower parts of the reservoir to light oils at the top, the points for individual measurements are much scattered. The scattering is less when measurements for wells north-east of and between the two large faults shown on Fig 1 are separated from the rest. It will also be noted that oils from these wells with large thicknesses of second sand show a different trend than the others. From the trends represented by the lines on Fig 1, and from

the comparatively few samples from the lower parts of the reservoirs, it appears that near the water table the hydrocarbon reservoir fluid in the Wara sand, in the main Burgan and north-east areas, and in the second sand are all much the same.

Measured saturation pressures plotted against elevation for samples from the main Wara sand pool are shown on Fig 3. At the top of the reservoir the oil was saturated with gas at original temperature and pressure. There was no free gas. Further down the oil was greatly undersaturated. Original in-place ratio varied from 600 cu ft/brl at the top to 100 cu ft at 4400 ft subsea, 66 ft above the oil–water interface. Samples, of unquestionable validity, from the immediate vicinity of the water table are difficult to obtain. None is available for the Wara sand reservoirs. From other evidence it is apparent that in the lowest part of the reservoirs the changes in fluid properties with elevation become rapid, ending in very heavy and viscous oil and with little or no gas in solution at the interface.

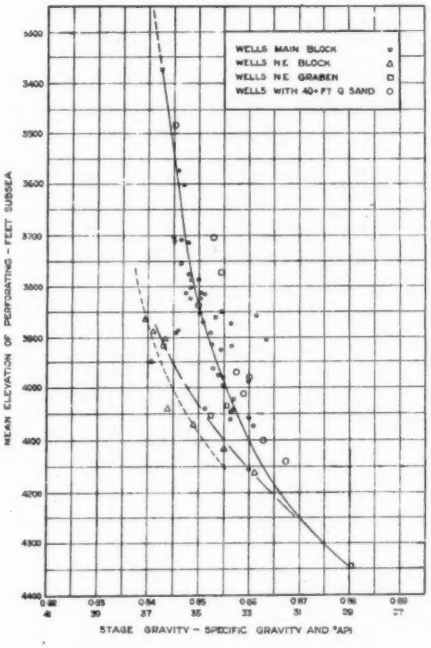
WELLS MAIN BLOCK
WELLS N.E. BLOCK
WELLS N.E. GRABEN
WELLS WITH 40+ FT G SAND
MEAN ELEVATION OF PERFORATING - FEET SUBSEA
STAGE GRAVITY - SPECIFIC GRAVITY AND °API

FIG 2
WARA SAND
Stage gravity *v.* depth, 1953.

Data on dissolved gas gravity for the Wara sand are not very satisfactory. It is sufficient to indicate that the gas gravity increases with depth as the oil becomes heavier and the quantity of gas in solution declines. The oil formation volume factor is largest near the top of the reservoir and decreases with increasing depth. The compressibility of the undersaturated oil is also greater in the upper part of the reservoir.

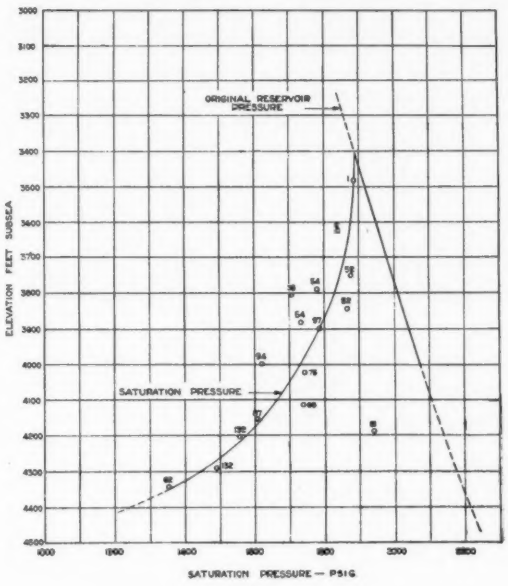

FIG 3
WARA SAND
Original reservoir and saturation pressures.

VARIATIONS IN RESERVOIR OIL VISCOSITY

Of all the properties of the reservoir fluids, the viscosity of the oil shows the greatest relative change with elevation. Oil viscosities are greatly affected by temperature. The reservoir is, of course, hotter at the bottom than at the top. The changes in fluid composition, however, very much more than offset this temperature increase. The oil viscosities in any of the Burgan reservoirs a few feet above the water table are five times or more the viscosities of the oil at the top.

The viscosities of the original reservoir oils plotted against elevation for the Wara, third, and fourth sands of the main Burgan field are shown as Fig 4. These curves all have a J shape. In the upper parts of the reservoir the viscosity changes slowly with depth. At lower elevations the change becomes more rapid. At the bottom, the curve of viscosity against elevation becomes almost flat. Samples of these sticky liquids are difficult to obtain, and producing wells are not ordinarily completed in this interval. Its properties are, therefore, inferred from a few samples, and from projections of the trends of data for the higher parts of the reservoir. A projection of the viscosity trend to the lower edge of the reservoir would indicate that at the original interface itself the reservoir hydrocarbon was semi-solid.

The fluid below the knee of the curves on Fig 4 is

sometimes called a "tar mat." Tarry globules, not homogeneous with the surrounding oils, have been observed in fluid samples and in Burgan cores. They are not confined to the bottom of the reservoir, but are most common there. It is of interest to note that it is

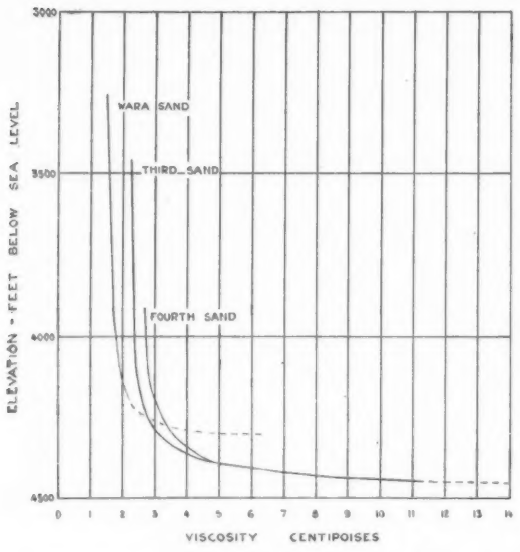

FIG 4

RESERVOIR OIL VISCOSITIES—MAIN BURGAN FIELD

in the longest oil column, in the Wara sand, that the layer of high-viscosity oil is apparently thickest. This would be the arrangement expected if all the reservoirs once contained equal proportions of the heavy, tarry materials and the lighter components. As these settled out to the bottom, the thickest tar zone would be in the longest column.

VARIATION IN FLUID PROPERTIES AS A GUIDE TO FLUID BOUNDARIES

Curves for oil gravity, gas gravity, in-place gas–oil ratios, and oil formation volume factor plotted against elevation also have the characteristic J shape. For the other properties the bend is less sharp than that of the viscosity–elevation curve. The total variation is also relatively smaller for the oil and gas gravities, and for the formation volume factor. At the interface the in-place gas–oil ratio may be nearly zero. This characteristic J shape may explain how variations in reservoir fluids, though considerable, might easily be overlooked. In most oil reservoirs, particularly those with thin oil columns, wells are apt to be opened for production only in the upper and middle parts of the oil band. The slight variations in these parts could easily escape notice, and no tests would be made nearer the water table, where the changes would be most rapid.

Recognition of this characteristic curve could be applied in estimating the extent of reservoirs, whose limits have not been defined by drilling. Starting with a discovery well at or near the top of the structure, increasing heavier oils should be observed in a series of wells progressively farther out and down structure. An abrupt change in the slope of the oil gravity or oil viscosity plotted against the elevation of the producing formation should indicate that a well at the next location would be marginal or outside the productive limits.

The gravities of the residual oils in cores from the Raudhatain discovery well in North Kuwait were estimated by measurement of the refractive indices. When these were plotted against elevation, the J shape was found to be repeated several times in a thick sandstone section with obscure shale breaks. These were thought to indicate the existence of separate oil bodies with distinct oil–water interfaces, an inference which has, in part, been confirmed by further drilling.

DISTRIBUTION OF RESERVOIR FLUIDS AS AN INDICATION OF RESERVOIR CHARACTERISTICS

Fig 5 shows measured saturation pressure against elevation for the Tensleep sand reservoir, Elk Basin field, Wyoming.[5] Fig 6 gives the same data as given

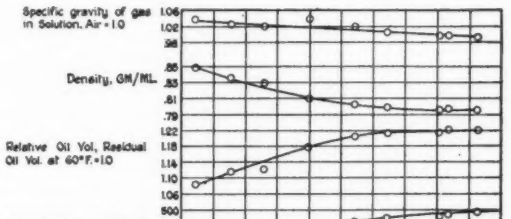

FIG 5

RELATIONSHIP OF OIL CHARACTERISTICS TO ITS LOCATION IN THE TENSLEEP RESERVOIR, ELK BASIN FIELD

by McCord [6] for the LL 370 reservoir, Bolivar coastal fields, Lake Maracaibo. In the Tensleep reservoir the measured saturation pressure varies regularly with elevation, with little deviation of measured value from a smooth curve. In the LL 370 reservoir the scattering is similar to, but far less than that shown on Fig 3 for the Wara sand.

The scattering for the Wara sand is far too large to be experimental error. Because of the extreme deviation of the saturation pressure of the fluid from Well BG. 81, another sample was taken from this well.

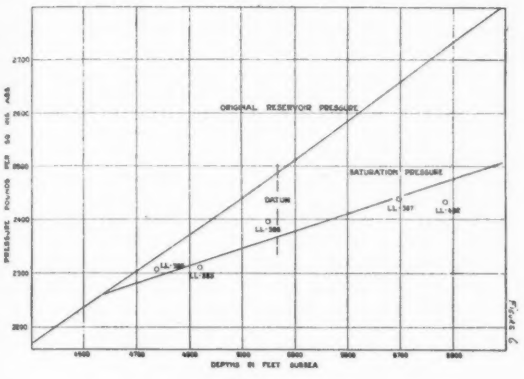

FIG 6

LL.370 RESERVOIR–PRESSURE DEPTH RELATIONSHIP

The saturation pressure was found to be essentially identical with that of the first sample. And there is similar scattering in other measured fluid properties. A reasonable explanation is to assume that the reservoir is extensively broken by barriers to free fluid flow. None of these has been completely effective in extended geologic time. Otherwise there would have been separate accumulations of oil, with different oil–water interfaces.

The gas caps in the Wara sand are at the top of the lower Ahmadi, Magwa, North-east Burgan, and Graben tops, and there is none at the crest of the higher main Burgan anticline. Also note on Fig 2 that while the oil at the top of the main Burgan structure is comparatively light, it is heavier than that just beneath the gas caps in North-east Burgan and the Graben. Still lighter oils occur below the larger gas caps in Magwa and Ahmadi, that in Ahmadi being the lightest of all. This is the distribution, which would be expected if the hydrocarbons accumulated by flow of gas, light oils, and heavier oils, already wholly or partly segregated along the underside of the cap rock. There are instances elsewhere of this distribution, with the only gas cap or the larger gas cap on the lowest of two or more structural apexes, with a continuous oil column between. The Coalinga Nose and Coalinga North-east fields in California are a well-known example.

Smaller pockets of gas and/or lighter oils might similarly be expected in smaller traps within the reservoir. Such traps could be formed by impermeable shale layers following the bedding but continuous over the crest of the structure but not over the whole productive area. They could also occur in sand lenses " pinching out " upward, or a combination of impermeable layers and small faults. Such traps must be numerous in the wide area covered by the productive Wara sands. The deviation of the characteristics of individual fluid samples from the general trends are thus apparently explained. Less deviation would be expected in the smaller and less complex LL 370 reservoir. In the Tensleep reservoir, which is very much smaller, and consists mostly of the clean, relatively uniform Tensleep sand, near perfect regularity would be expected.

COMPARISON OF OILS IN THE WARA, THIRD, AND FOURTH SANDS, MAIN BURGAN

If the third and fourth sands are separated from the Wara and from each other by stratigraphic barriers to fluid migration, completely effective in geologic time over most but not all of the productive area, the oils in the upper parts of these reservoirs should be different at the same subsea elevation. Towards the bottom they should tend to be more nearly the same. The gravities of the flow-line oils from these sands in the main Burgan field are shown in Fig 7.

Fig 8 shows measured saturation pressures and original reservoir pressure against elevation for the

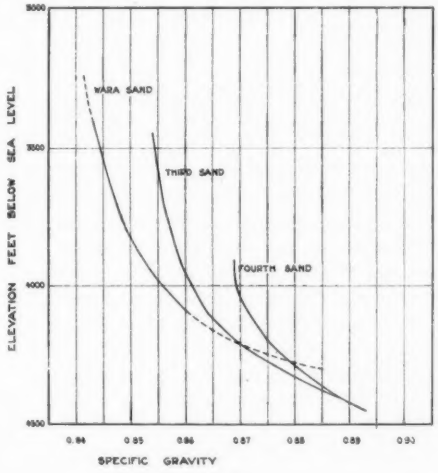

FIG 7

FLOW-LINE OIL GRAVITIES, MAIN BURGAN FIELD

fourth sand. A line has been drawn for the probable trend of the saturation pressure. Other considerations than the experimental data shown were applied in its placement. All the oil of this reservoir was undersaturated at original temperature and pressure. The saturation pressure of three of the samples was far higher than that for others at nearly the same

elevation. A higher saturation pressure indicates either a heavier oil or a higher gas–oil ratio or both. These samples are from wells near the centre and crest of the field, where the trapping of pockets of gas and light oil would be most probable. The fourth sand is generally a massive and relatively clear sand with little shale. On all the electric logs at about its centre there is, however, a prominent indication of a thin but persistent shale.

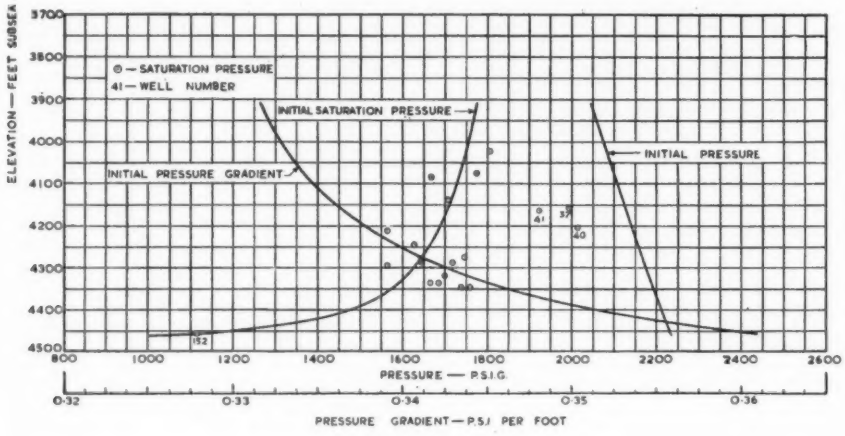

FIG 8

BURGAN FIELD (Fourth sand)—INITIAL RESERVOIR AND SATURATION PRESSURES AND PRESSURE GRADIENT

VARIATION WITH ELEVATION OF THE PROPERTIES OF INTERSTITIAL WATER

Not only do the properties of the hydrocarbons in the Burgan reservoir vary with elevation, but similar changes have also been found in the interstitial water. The interstitial brines which are found in all, or practically all, oil and gas reservoirs are solutions of various salts, chiefly sodium chloride in water. They are also in a gravitational field, and therefore the concentration of the heavier components, in this case the dissolved solids, should become greater at greater depth. This is found to be the case.

The salinity of the interstitial water in the Burgan oil reservoirs is known from measurements of the salt content of water in cores. It can also be estimated from the resistivity as shown on the electric logs. The water at the top of the Wara reservoir in Burgan has a salinity, measured as sodium chloride, of 56,000 ppm. The salinity increases to 147,000 ppm at the oil–water interface. So far as is known the variation is reasonably regular; this apparent regularity may, however, be only the result of very incomplete data. From the non-productive well at Umm Gudair and from drilling in North Kuwait it is known that, as would be expected, the increase in the salt content of the formation water continues outward and downward from the edges of the field.

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RELAXATION BEHAVIOUR OF OILS

On 16 and 17 February 1959 a two-day symposium was held at the Institute of Petroleum, 61 New Cavendish Street, London, W.1, on "Relaxation Behaviour of Oils with Special Reference to Gear, Ball, and Roller Bearing Lubrication." The meeting was arranged by members of the Mechanical and Electrical Engineering Departments of the City and Guilds College, Imperial College of Science and Technology, University of London. The meeting was opened by Dr E. B. Evans, Honorary Editor, Institute of Petroleum, who then invited Dr A. Cameron to take the Chair.

Four papers were presented and discussed as follows:

1. "Survey of the Present Position of the Theory of Rolling Contacts." Dr A. Cameron (Imperial College of Science, Mechanical Engineering Department).
2. "Visco-Elastic Behaviour of Lubricating Oils under Cyclic Shearing Stress." Dr J. Lamb and A. J. Barlow (Imperial College of Science, Electrical Engineering Department).
3. "The Elasto-Hydrodynamic Problem." Professor E. Saibel (Rensselaer Polytechnic Institute, Troy, New York).
4. "Graphical Integration of the Maxwell Fluid Equations and their Application." R. F. Crouch and Dr A. Cameron (Imperial College).

Paper 4 is published in full in this issue of the *Journal*, and it is hoped that complete versions of the other papers may become available. In the meantime summaries of the first three papers are given below, together with the discussion on all the papers.

SUMMARIES

1. The first paper, "Survey of the Present Position of the Theory of Rolling Contacts," was read by Dr Cameron, who said that the theory of rolling contacts was just beginning to be based on a reasonable theoretical foundation, as it was only recently that experimental methods had been developed which enabled an estimate of the oil film thickness to be made.

In the past few years careful measurements of the oil film had been made by Crook,[1] using a capacity method to measure the oil film thickness between disks. The value obtained was about 10^{-4} inches. Siripongse, Rogers, and Cameron [2] for the four-ball machine, and also MacConochie and Cameron,[3] both using a method involving measuring the discharge potential, found about the same value of the oil film thickness as was reported by Crook.

Finally, a new development of the standard method of measuring the resistance of oil as a measure of the oil film thickness has been published by Shawki and El Sisi.[4] It was found that adding 4 per cent of a petroleum sulphonate to the oil dropped its specific resistance very considerably and that the oil exhibited an ohmic resistance. This enabled oil film thickness measurements to be made. It seems a promising method, but further work is needed on it.

Using the thickness measurements obtained by the discharge method, Siripongse and Cameron attempted to correlate the friction measured in the four-ball machine with Newton's laws of viscosity. Grubin [5] had shown that the contact zone was flat and parallel under conditions of high Hertzian pressure, and the pressure curve is approximately the same as that of the Hertz elastic case. Using this fact, they obtained a fairly reasonable correlation between the pressure required to produce the viscosity evaluated from their experiments and the Hertzian pressure. There were two possible reasons for the deviation from complete correlation which was observed. This showed itself as a speed effect, and could have been due either to an incorrect choice of viscosity and the pressure–viscosity coefficient, or else to the effect of the visco-elasticity of the lubricant. In all these calculations the effect of the pressure–viscosity coefficient is dominant, and the lack of a reliable knowledge of it imposes a considerable limitation on any calculations.

Further developments in the elasto-hydrodynamic problem, carrying on from Grubin [5] and Petrusevich,[6] are to be reported later in the symposium. It seems that this problem is now within sight of solution.

2. The next paper was by Dr J. Lamb and A. J. Barlow, who described the work they carried out in the Electrical Engineering Department of Imperial College on the "Visco-Elastic Behaviour of Lubricating Oils under Cyclic Shearing Stress." The shear properties of three base-stock lubricating oils supplied by the Thornton Research Centre have been measured through their relaxation region: the oils were selected to be of high, medium, and low viscosity index. Information on the hydrocarbon-type distribution and the molecular weight distribution of the aromatic constituents, together with pressure–viscosity data, was also provided by the Thornton Research Centre.

Using ultrasonic techniques, the shear impedance of each oil, defined as the ratio of shear stress to velocity, has been measured in the frequency range 10^4 to 10^8 c/s at temperatures from $+30°$ to $-56°$ C and for hydrostatic pressures up to 1000 atmospheres. At 30° C, relaxation commences above 10^7 c/s; by

reducing the temperature or increasing the pressure on the oil, relaxation occurs at lower frequencies. The reduction principle originated for polymers by Ferry was found to be valid for the oils; for a given oil the measurements at various frequencies and temperatures could be reduced to a single " universal " curve for each component of the complex shear modulus when plotted against the product of frequency and viscosity. In this way an extension of the frequency range could be simulated by changing the temperature, and the whole relaxation region covered. Moreover, results obtained at different pressures fit on to the same universal curve, at least for pressures up to 1000 atmospheres, which is the highest value employed so far in the experiments.

The complex shear modulus, defined as the ratio of shear stress to shear strain, was calculated from the impedance curves. Below the relaxation region the oils behave as ordinary viscous (Newtonian) liquids; with increasing frequency the viscous contribution to the shear strain diminishes, and elastic effects become important. Above the relaxation region the oils behave as glass-like solids, having shear rigidities just below 10^{10} dynes/cm^2. The shear modulus curves for each oil have been analysed in terms of a distribution of Maxwell relaxation times or frequencies; the spectra are rather similar, each extends over about five decades of frequency and has an irregular shape. There is no correlation of the spectrum with the molecular weight data, but some tentative conclusions can be drawn from a comparison of the shape of the spectrum with the hydrocarbon types present. The high and medium viscosity index oils have similar fractional compositions, they contain about 66 per cent saturates, 20 per cent monoaromatics, 9 per cent diaromatics, and 5 per cent triaromatics; their relaxation spectra are also similar, with a peak around 10^{11} c/s on the universal curve normalized to 30° C. The low viscosity index oil is predominantly aromatic, its spectrum peaks between 10^8 and 10^9 c/s. Thus the constituents are associated with different parts of the spectrum; by extending the argument it is inferred that the principal contributions of the hydrocarbon types are, in ascending order of frequency, triaromatics, diaromatics, monoaromatics, and saturates. This appears consistent with the molecular interpretation of shear relaxation, the largest molecules being the first which fail to follow the stress cycle as the frequency is increased. The importance of relaxation in lubrication lies in the effects of temperature and pressure on the viscosity of an oil. The limiting shear rigidities of the oils are similar to those of other organic liquids, and to a first approximation are independent of temperature and pressure. As a useful guide, relaxation becomes important when the time of stress application is comparable with the " average " relaxation time given by the ratio of viscosity to shear rigidity; for approximate calculations the shear rigidity may be taken as 10^{10} dynes/cm^2. The variation in relaxation time is then almost entirely governed by the variation in static viscosity.

The problem of predicting the practical behaviour and properties of an oil under the conditions encountered in lubrication of high-speed gears and bearings is highly complicated: present theory rests almost entirely on the assumption of linear behaviour. In the present work it has been shown where relaxation effects are important. The validity of the universal curve has been established only for pressures up to 1000 atmospheres, and it remains to verify that extrapolation to pressures of 10,000 atmospheres—such as are encountered in high-speed lubrication—is permissible. Work along these lines is in progress.

Little information is available on the shear elasticity of pure organic liquids, and further work is being carried out to investigate the connexion between the visco-elastic properties and chemical composition, both as regards the shape of the relaxation spectrum and the limiting value of the high frequency rigidity.

Results were also described for a series of silicone (MS. 200) liquids: comparing the behaviour of the oils with that of the silicone fluid having approximately the same viscosity at 30° C shows that relaxation in the silicone occurs at considerably lower frequencies. This is attributed to a configurational rigidity of the order of 10^6 dynes/cm^2 associated with a relaxation in which the long-chain molecule as a whole is unable to follow the stress alternation. This effect has not been observed in the oils which have much shorter molecular chains for a given static viscosity.

3. Professor Saibel then spoke on the work he and Professor F. F. Ling, both of Rensselaer Polytechnic Institute, at Troy, New York, are doing on " The Elasto-Hydrodynamic Problem." Under the assumption of a quasi-stationary state, the neglect of inertia terms, and a similarity principle, the equation relating shear stress and pressure in the fluid is obtained. This is combined with the relationship between stress and strain in a Maxwell fluid and the continuity equation leading to an integral equation for the velocity distribution. The solution is effected by a method of successive substitutions and linearized by assuming the time of relaxation of the fluid to be small in comparison with the time of transit of the fluid across the bearing. Sufficient freedom results in the solution to impose the requisite boundary conditions as well as entrance and exit conditions.

He then described in the second part of his talk several lines of attack on the problem of a lubricant flowing between elastic surfaces in which the viscosity is a function of the pressure, and the deformation of the surfaces is comparable in magnitude with the original film thickness. Professor Saibel described: (*a*) a perturbation method of solution not depending on the deformation being small; (*b*) an inverse method

in which the final film thickness was presumed known and the initial state found; and (*c*) a method which combined the hydrodynamic pressure development with the differential equation governing the deflection of the surfaces giving a differential equation in a single variable, namely, the final film thickness.

4. This paper is now published in full.

DISCUSSION

The discussion was opened by **Dr D. Dowson** and **Dr G. R. Higginson** (University of Leeds), who described their approach to a theoretical solution of the elasto-hydrodynamic problem. They considered that the question of satisfying simultaneously the

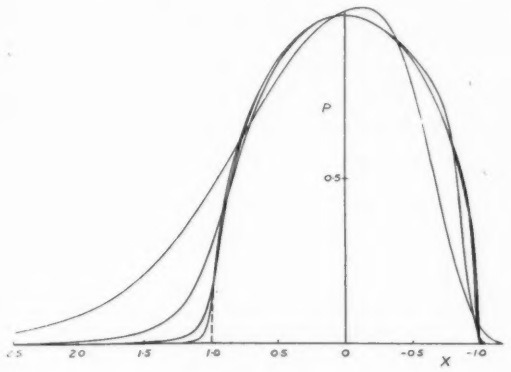

FIG 1

elastic and hydrodynamic requirements of the problem was sufficiently complicated to justify the selection, in the first instance, of a minimum number of variables. Because the problem is associated with the transmission of forces in machine elements of a geometrical form which requires high local pressures, the elasticity of the solids and the influence of pressure on the lubricant viscosity must clearly be introduced at an early stage. Later, thermal effects in the solids and the lubricant, compressibility, inertia forces, and non-Newtonian behaviour could be considered.

For large elastic deformations the pressure curve over most of the zone must be close to the Hertzian pressure distribution for dry contact. A " deformation ratio " defined as the ratio of the local elastic flattening to the oil film thickness is therefore of value in classifying available solutions. The solutions of Weber and Saalfeld [7] and Saibel [8] cover deformation ratios up to unity. Petrusevich [6] has presented solutions with deformation ratios up to 80. The authors have recently obtained solutions for cylindrical solids lubricated under isothermal conditions which range from deformation ratios of 1 to 60 (Fig 1). These solutions clearly demonstrate the approach towards the Hertzian pressure curve as the deformation ratio increases. The deformation ratio was calculated on the basis of the centre-line film thickness, and in each case the minimum film thickness was 20–25 per cent smaller.

Professor Petrusevich (Academy of Sciences, Moscow) commented that Dowson and Higginson's solution did not have the sharp peak at the end of the contact zone his solution [6] had, though the sudden diminution of oil film thickness was there. He wondered if the peak would appear when these authors went to the high loads he had studied.

Dr Dowson said they had noticed the absence of the peak, but doubted if it would appear even at high loads.

Professor H. Blok (Technische Hogeschool, Delft) commented on Crouch and Cameron's paper that the temperature variation in a film with visco-elastic lubricant will in general differ from that in a film with a Newtonian lubricant. In view of the fact that in either case Crouch and Cameron disregarded such a variation, it remains to be seen whether the comparison of the two relevant distributions of shearing stresses, and even of their relative position (including their general level, or, say, average), will remain valid in reality.

Dr Cameron in reply said that they wanted to see if conditions of lubrication in these cases were even in the zone where relaxation could play any part at all, so the very simplest starting conditions were used.

Professor Blok then made some general remarks about the theory of visco-elasticity lubrication. In his 1957 paper A. Milne [9] treated two cases considered by him to represent the extremes conceivable, *i.e.* one case in which the visco-elastic lubricant enters the film unstressed, and the other in which it enters in a relaxed condition. He succeeded in showing that in either case the load capacity is smaller than would obtain for a Newtonian lubricant under otherwise comparable conditions. It is thought, however, that there may well be cases lying outside Milne's range. Thus there might still be a possibility that in certain cases a visco-elastic fluid shows a greater load capacity than a Newtonian one.

All in all, it would appear that, as Archard and Crook have already shown for elasto-hydrodynamic lubrication, with visco-elastic lubricants also the state of the lubricant at the entry of the film is an influential factor of considerable importance. It might well control the hydrodynamic formation of film pressures, and thereby the load-carrying capacity, to a very great extent.

Dr J. F. Archard (Associated Electrical Industries, Aldermaston) said that it had been assumed that relaxation effects become important when the relaxation time was comparable with the transit time. If transit through the whole contact region is considered, this condition means that an oil viscosity of the order of 10^4 poise is required. This might conceivably be

achieved through the change of viscosity with pressure. However, both theory and experiment[1,10] suggest that, when any appreciable sliding occurs, the oil viscosity is very much less than this because viscous heating raises the oil temperature by as much as 100° or 200° C; thus in this basis relaxation effects appear unlikely. There is strong theoretical and experimental evidence[1,10,11] that the oil film thickness is effectively determined by conditions existing over a small region on the entry side. If this region only was considered, relaxation effects might be possible, as the viscosity was less because of the lower pressures, but there was practically no temperature rise and the effective transit time was very much smaller.

Dr Cameron, in summing up, said that it seemed to be agreed that this symposium had been useful in allowing those working in this field to know what other people were doing.

The two subjects needing further study were: (1) does Maxwell's equation hold as well for large strains as Lamb and Barlow showed it does for small ones, and what is the limiting strain?; (2) there is a very pressing need for a good correlation between the temperature-viscosity characteristics of an oil and its pressure-viscosity coefficient.

A. CAMERON

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GRAPHICAL INTEGRATION OF THE MAXWELL FLUID EQUATION AND ITS APPLICATION *

By R. F. CROUCH † and A. CAMERON †

SUMMARY

Maxwell's equation for the friction of a visco-elastic fluid with viscosity varying with pressure is derived. The solution of this equation, giving the friction for the conditions met in gears, (a band contact zone), is achieved graphically by the method of isoclinals. It is also extended to a circular contact zone, (spheres). It is found that the friction deviates from the pure Newtonian value when the relaxation number T gets beyond unity. T is defined as $\left(\frac{\eta_{max}/G}{b/U}\right)$, *i.e.* $\frac{\text{Peak viscosity/shear modulus}}{\frac{1}{2}\text{ Hertzian width/speed}}$, which is $\left(\frac{\text{Relaxation time}}{\frac{1}{2}\text{ transit time}}\right)$. This is applied to some gear scuffing experiments of Borsoff. It is not certain whether they are in the region where visco-elasticity plays a part. Further consideration shows that while it is unlikely that the oil film formation is affected by visco-elasticity, the friction may be.

Symbols

A	Pressure–viscosity parameter $A \equiv \alpha p_{max}$
b	Half-width of Hertzian contact
B	Alternative pressure viscosity parameter
e	Displacement
$F_{N,M}$	Total frictional force under a Newtonian, Maxwell fluid
G	Shear modulus (for oils $G = 10^{10}$ dynes/cm^2)
h	Film thickness
L	Length of contact along direction normal to motion
M	Ratio F_N/F_M
p	Pressure
Q	Non-dimensional friction $Q \equiv Fh/Gb^2L = \int S dx^*$
r	Radius of Hertzian contact
S	Non-dimensional shear parameter $S \equiv \tau^* h/b$
T	Relaxation number $T \equiv \frac{\eta_{max}/G}{b/U}$
u	Velocity of oil particle
U	Surface velocity
x	Co-ordinate in direction of motion
X	Alternative co-ordinate $X \equiv \sqrt{\frac{10}{B}} . x^*$
y	Co-ordinate normal to direction of motion
Y	Ratio S/T
z	Co-ordinate in direction of film thickness
α	Pressure viscosity coefficient
γ	Angle of shear
η	Viscosity
η_o	Viscosity at atmospheric pressure
η_p	Viscosity at pressure p
η_{max}	Maximum viscosity at $p = p_{max}$
τ	Shear stress
*	Indicates a non-dimensionalized quantity, namely, $x = bx^*$, $z = hz^*$, $h = bh^*$, $\tau = G\tau^*$, $u = Uu^*$, $\eta = \eta_{max}\eta^*$

INTRODUCTION

It has been suggested [1] that the elasticity of the lubricant when carrying a load is of importance. Fromm and others [2] have dealt with the formulation of the three-dimensional equations of such visco-elastic fluids, and this is also the subject of a contribution by Broer.[3] The three-dimensional formulation is extremely complex, and no conclusion seems to have yet been reached on it. In the uni-directional case the problem is relatively simple, and the equations will be derived below.

The liquid studied here is a Maxwell fluid, *i.e.* a fluid which may be considered as having both elastic and viscous properties which are additive. It may be thought of as a spring and dashpot in series. Lamb and Barlow [4] have found that this simple system describes the properties of oil over a very large range of viscosities and temperatures. Their measuring technique, employing a vibrating crystal, involves extremely small amplitudes—well below 10^{-6} cm—and the applicability of the Maxwell fluid concepts to oils which undergo large strains has yet to be investigated.

An important paper dealing with the load-carrying capacity and the friction for slider bearings with a linear velocity gradient is by Milne.[5] In the present paper the friction equations for rolling contacts are solved graphically using Milne's assumption of a linear velocity profile, the object here being to see where the fluid diverges from the pure Newtonian condition and starts behaving as a Maxwell or visco-elastic liquid. The assumption of the linear velocity distribution is therefore not too illogical, as the requirement is to find where the visco-elasticity starts to play a part.

An extremely important consideration is, however, the inclusion of the influence of pressure on viscosity. This first gets over a difficulty encountered in this class of work, concerning the degree of relaxation of the fluid entering the lubrication zone; and secondly, without the pressure–viscosity term, the fluid would never be in a state where elasticity is important.

In this paper, then, the equations for a Maxwell

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† Dept of Mechanical Engineering, City and Guilds College, London, S.W.7.

fluid will first be derived, then the solution for line contact—disks or gears—will be explained and then extended to balls. Finally, it will be applied to some gear research by Borsoff.[6] Originally the work was started to study the four-ball results of Cameron and Siripongse,[7] but it was soon found that the speeds at which they worked were too low for visco-elasticity to play any part. The theoretical results on balls are, however, included, as they will be of interest should studies be made of high-speed ball bearings.

DERIVATION OF EQUATIONS

First consider a small element of pure viscous fluid of viscosity η and of sides dx, dz subjected to a shearing

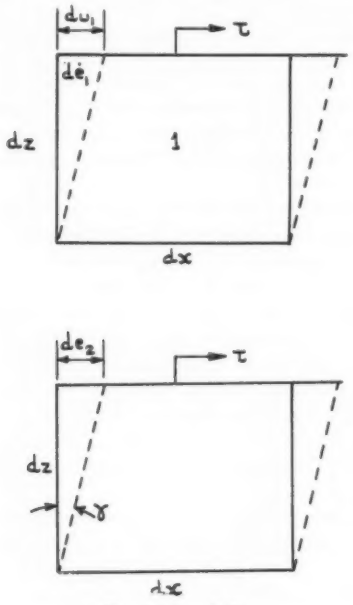

FIG 1 (*a*) and (*b*)

force τ as shown, Fig 1 (*a*). The equation for the velocity gradient $\left(\frac{du_1}{dz}\right)$ is given by the Newtonian equation

$$\frac{du_1}{dz} = \frac{\tau}{\eta}$$

or

$$\frac{d\dot{e}_1}{dz} = \frac{\tau}{\eta}$$

where de_1 is the displacement and $\dot{e}_1$ its time derivative.

Secondly, consider an elastic element subjected to a shearing force τ. If it has a shear modulus G, the angle of shear γ is (Fig 1 (*b*))

$$\gamma = \frac{\tau}{G} = \frac{de_2}{dz}$$

where de_2 is the elastic displacement. If τ varies with time, then $\frac{\dot{\tau}}{G} = \frac{d\dot{e}_2}{dz}$, where the dot shows the time derivative. If all these displacements are small they can be added thence by superposition $de = de_1 + de_2$, or

$$\frac{du}{dz} = \frac{d\dot{e}_1}{dz} + \frac{d\dot{e}_2}{dz}$$

Thus

$$\frac{du}{dz} = \frac{\tau}{\eta} + \frac{1}{G}\frac{d\tau}{dt}$$

Instead of $\frac{d\tau}{dt}$ it is more convenient to write

$$\frac{d\tau}{dt} = \frac{d\tau}{dx}\frac{dx}{dt} = \frac{d\tau}{dx}u$$

so the equation for a Maxwell fluid is

$$\frac{\partial u}{\partial z} = \frac{\tau}{\eta} + \frac{u}{G}\frac{\partial \tau}{\partial x}$$

This equation must be treated numerically, so a non-dimensional form is more convenient, and in order to obtain this the following quantities are defined:

$$x = bx^*$$
$$z = hz^*$$
$$h = bh^*$$
$$\tau = G\tau^*$$
$$u = Uu^*$$
$$\eta = \eta_{\max}\eta^*$$

where b is some characteristic length of the system measured in the direction of motion. Here the half width of Hertzian contact will be chosen. h is the film thickness which will be discussed later. G has already been defined as the shear modulus. Lamb and Barlow have shown that this is equal to about 10^{10} dynes/cm^2 for almost all oils. U is the surface velocity and $\eta_{\max}$ the maximum viscosity assuming the viscosity is influenced by pressure. Substituting all these into the last equation

$$\frac{U}{h}\frac{\partial u^*}{\partial z^*} = \frac{G\tau^*}{\eta_{\max}\eta^*} + \frac{Uu^*}{b}\frac{\partial \tau^*}{\partial x^*}$$

or

$$\left(\frac{b}{h}\right)\frac{\partial u^*}{\partial z^*} = \left(\frac{Gb}{\eta_{\max}U}\right)\frac{\tau^*}{\eta^*} + u^*\frac{\partial \tau^*}{\partial x^*}$$

Now $\frac{\eta_{\max}/G}{b/U}$ is defined as T, which is called the relaxation number, whence the equation reads

$$\frac{b}{h}\frac{\partial u^*}{\partial x^*} = \frac{1}{T}\frac{\tau^*}{\eta^*} + u^*\frac{\partial \tau^*}{\partial x^*}$$

Now both $(\eta_{\max}/G)$ and (b/U) have units of time. $(\eta_{\max}/G)$ is often called the relaxation time of the fluid. (b/U) is merely the half transit time of a particle of fluid through the contact zone. Thus T, the relaxation number, is the ratio of the peak relaxation time to the half transit time.

It is usual to express the change of viscosity with pressure as

$$\eta_p = \eta_o e^{\alpha p}$$

where η_p = viscosity at pressure p;
η_o = viscosity at atmospheric pressure;
α = pressure viscosity coefficient.

Thus $\eta_{max} = \eta_o e^{\alpha p_{max}}$

so $\eta = \eta_o e^{\alpha p} = \eta_{max}\eta^* = \eta_o e^{\alpha p_{max}}\eta^*$

Hence $\eta^* = e^{\alpha p}/e^{\alpha p_{max}}$

The pressure distribution can be taken as $p = p_{max}(1 - x^2/b^2)^{\frac{1}{2}}$ or as $p = p_{max}(1 - x^2/b^2)$, these functions being graphically similar, but actually the second one is used, as explained below.

Hence $$\eta^* = e^{\alpha p_{max}(1 - x^2/b^2)}/e^{\alpha p_{max}}$$
$$= e^{-\alpha p_{max} x^2/b^2} = e^{-p\alpha_{max}{}^2}$$

This is also non-dimensional as α has the units of (pressure)$^{-1}$. The equation now reads

$$\frac{b}{\bar{h}}\frac{\partial u^*}{\partial z^*} = \frac{\tau^*}{\bar{T}} e^{\alpha p_{max} x^{*2}} + u^* \frac{\partial \tau^*}{\partial x^*}$$

Before discussing the solution of this, the use of the pressure distribution $p = p_{max}(1 - x^2/b^2)$ is justified.

PRESSURE DISTRIBUTION

It has been shown by Grubin (quoted in ref. 7) that when the pressure between contacting surfaces is high, as it is in gear teeth or ball bearings, the pressure distribution of the lubricant film becomes Hertzian. This argument has been given by Cameron and Siripongse.[7] The recent paper by Dowson and Higginson [8] on the elasto-hydrodynamic problem amply confirms this. It is normal to suppose that the pressure distribution is Hertzian, *i.e.* $p = p_{max}(1 - x^2/b^2)^{\frac{1}{2}}$, *i.e.* the pressure is semi-elliptical, which means the slope dp/dx at the edge of the contact zone, where $x = b$, is infinite. The work of Grubin shows that the slope at this point is finite, and for this reason a parabolic law, $p = p_{max}(1 - x^2/b^2)$, was used. The differences are not very great, certainly no greater than the approximation used to obtain a solution.

SOLUTION OF THE EQUATION

The approximation already discussed is to write $\left(\frac{\partial u}{\partial z}\right) \equiv \frac{U}{\bar{h}}$ this makes $\left(\frac{\partial u^*}{\partial z^*}\right) \equiv 1$, so the equation simplifies to

$$\frac{b}{\bar{h}} = \frac{\tau^*}{\bar{T}} e^{\alpha p_{max} x^{*2}} + u^* \frac{\partial \tau^*}{\partial x^*}$$

Furthermore, the frictional drag is required only on the surface where $u = U$, *i.e.* where $u^* = 1$, so if for simplicity αp_{max} is written as A

$$\frac{b}{\bar{h}} = \frac{\tau^*}{\bar{T}} e^{Ax^{*2}} + \frac{d\tau^*}{dx^*}$$

A further simplification is to write $\tau^* \frac{h}{b} = S$

So $$1 = \frac{S}{\bar{T}} e^{Ax^{*2}} + \frac{dS}{dx^*}$$

This is now the equation that requires solving.

In view of the extremely wide range of $e^{Ax^{*2}}$, from unity to about e^{20} or $4{\cdot}85 \times 10^8$, a graphical method is more convenient than a numerical one. The method of isoclinals was suggested to the authors by Professor W. G. Bickley and S. Michaelson.

The equation is written as follows

$$1 = \frac{S}{\bar{T}} e^{Ax^{*2}} + \frac{dS}{dx^*}$$

so $$\frac{S}{\bar{T}} = \left(1 - \frac{dS}{dx^*}\right) e^{-Ax^{*2}}$$

The first value of A, *i.e.* of αp_{max} used was 10, and a graph was drawn of e for $x^* = -1$ to $+1$. Next a family of curves of the error function $e^{-10x^{*2}}$ was drawn to suit the particular T solution required. These solutions were in fact carried out for $T =$ 0·01, 0·1, 1·0, 10, 100, 1000, and 10,000, the area under the solution giving $\int_{-1}^{1} S\, dx^*$, a measure of the force $\int \tau\, dx^*$. These areas refer only to the $A = 10$ solution, but, as can be appreciated, the same results can be adjusted to correspond with any values of A. A typical curve is shown in Fig 2 for $A = 20$ and $T = 1$.

For a general value of $A = B$, say, the axes can be altered to fit new error function curves corresponding to those for the solution with $A = B$. Taking as the standard $A = 10$, then for $A = B$ to be dealt with the error envelopes on the isoclinal diagram become defined by a new co-ordinate X, where $BX^2 = 10x^{*2}$ or $X = \sqrt{\frac{10}{B}}\, x^*$. So, dealing with the original equation putting $\frac{S}{\bar{T}} = Y$,

$$Y = \left(1 - T\frac{\partial Y}{\partial x^*}\right) e^{-Ax^{*2}}$$
$$= \left(1 - \sqrt{\frac{B}{10}}\, T\, \frac{\partial Y}{\partial X}\right) e^{-Bx^2}$$

Hence plots for $A = 10$ (standard) give solutions for all T values provided $\frac{\partial Y}{\partial X} T =$ the slope of the error

function which the solution is crossing. The area under the solution is then $\int YdX$ and the required quantity $\int Sdx^*$ for $A = 10$, the standard solution, is given by

$$Q \equiv T \int YdX \equiv \int Sdx^*$$

Now these alterations in the axes to incorporate all values of A mean that the area values are altered. When altering the x^* co-ordinate to X in moving from solutions for $A = 10$ to $A = B$, each value of x^* actually reads $\sqrt{\frac{10}{B}}\,x^*$, so the area is altered by this factor. But this variation means that the slope of the isoclinals is changed also, and so the value of T must be adjusted to obtain the correct solution. Therefore the relaxation number must be multiplied by $\sqrt{\frac{10}{B}}$, and as T appears in the final area Q, then the area values must be multiplied by $\left(\frac{10}{B}\right)$ to obtain the areas for $A = B$ solutions.

RESULTS OF COMPUTATION

The standard values of Q and relaxation number T for $A = 10$ are

$T =$	0·01	0·1	1·0	10	100	1000	10,000
$Q =$	0·0055	0·0544	0·322	0·81	1·36	1·86	1·98

As explained above, to obtain results for $A = B$, the value of T is multiplied by $\sqrt{\frac{10}{B}}$ and Q multiplied by $\left(\frac{10}{B}\right)$.

As an example, if a curve of T against Q is required for $A = 20$ instead of $A = 10$, the figures will be as follows. The original T row must be multiplied by $\sqrt{\frac{10}{20}}$ and the Q row by $\frac{10}{20}$ and will now appear as:

$T =$	0·00707	0·0707	0·707	etc.
$Q =$	0·00275	0·0272	0·161	etc.

The significance of these results is explained later.

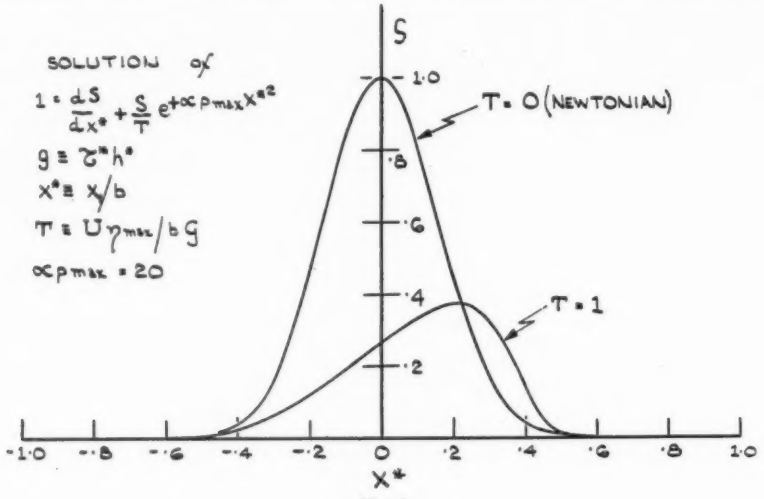

FIG 2

VALUE OF THE TOTAL FRICTIONAL FORCE F FOR A BAND

The aim of all this work is to calculate the total frictional force F over the contact zone. If the shear stress τ has been calculated, then $F = \int_0^L \int_{-b}^{+b} \tau dx dy$ where the contact area extends from O to L and from $-b$ to $+b$. If τ does not vary in the y direction, *i.e.* for a band, then

$$F = L \int_{-b}^{+b} \tau dx$$

Referring back to the equations,

$$S = \tau^* \frac{h}{b} = \frac{\tau}{G} \frac{h}{b}$$

where τ is the shear stress, G the shear modulus, h the film thickness, and b the half width of contact.

Hence $$Q = \int_{-1}^{+1} Sdx^* = \frac{h}{b} \frac{1}{Gb} \int_{-b}^{+b} \tau dx$$

Thus $$\frac{F}{L} = \frac{Gb^2}{h} \cdot Q$$

SOLUTION FOR SPHERES

These results so far have not considered any variation in the y direction. They are extended to spheres in the following manner.

The pressure distribution in a circular contact is taken as $p_{max}(1 - x^2/r^2)$, where r is the radius of contact. The area of contact is divided in strips

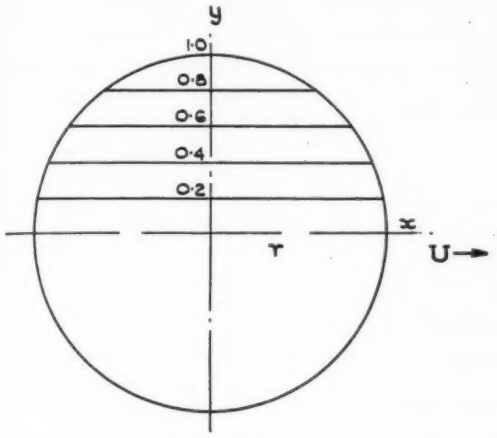

FIG 3

(Fig 3). The half length of contact for $y = 0$ is r, but in general it is

$$r_y = r\sqrt{1 - y^2/r^2}$$

The value of the peak pressure $p_{y_{max}} = p_{max}(1 - y^2/r^2)$, where p_{max} is the peak pressure at $y = 0$. Defining $y = ry^*$ then

$$p_{y_{max}} = p_{max}(1 - y^{*2})$$

The peak viscosity at any value of y is $\eta_o e^{\alpha p_{y_{max}}(1-y^{*2})}$, whence the value of T at y, T_y, referred to T_o the value of T at $y = 0$, is

$$T_y = \frac{\eta_{max\,y} U}{Gry^*} = T_o \frac{e^{-\alpha p_{max}(1-y^{*2})}}{\sqrt{1 - y^{*2}}}$$

The value of T_y for any point on the y axis for various values of T_o can then be calculated. From this the value of the total area $\int Qdz^*$ can be calculated, using the values of Q already calculated.

Consider any strip parallel to the x axis whose centre is at y. The friction in the x direction is as before

$$F = \frac{Gb^2LQ}{h}$$

where now L = strip width, which here is $r/5$

and $$b = \sqrt{r^2 - y^2}$$

T_y is already found and also the corresponding value of Q.

The friction of contact is then obtained by integrating the individual strip frictions by Double-Simpson. The total friction is, of course, the sum of the two equal halves.

The results of this integration given as $\int Qdz^*$ for various T and αp_{max} values, are tabulated below:

$\int Qdz^*$

T	For $\alpha p_{max} = 20$	15	13·3	10	5	2
10	0·284	0·412	0·455	0·720	1·72	4·56
5	0·216	0·321	0·349	0·532	1·27	—
2	0·141	0·205	0·221	0·328	0·759	—
1	0·094	0·132	0·142	0·215	0·485	—
0·5	0·059	0·082	0·008	0·128	0·277	—

RATIO OF FRICTION FOR NEWTON FLUID/FRICTION FOR MAXWELL FLUID

The ratio of the frictional drag F_N for a purely Newtonian fluid and that for a Maxwell fluid F_M is next obtained, for a line contact.

Let $F_N/F_M \equiv M$

$$F_N = L\int_{-b}^{+b} \tau dx = \frac{U\eta_{max}}{h} L\int_{-b}^{+b} e^{-Ax^2/b^2} dx$$

which can be obtained directly from the Newtonian equation without any elastic term or

$$F_N = \frac{U\eta_{max} bL}{h}\int_{-1}^{+1} e^{-Ax^{*2}} dx^*$$

Now the integral of the error function has a limit

$$\int_{-1}^{+1} e^{-Ax^{*2}} dx^* \longrightarrow \sqrt{\frac{\pi}{A}} \text{ if } A > 4$$

so that $$F_N = \frac{U\eta_{max} bL}{h}\sqrt{\frac{\pi}{A}} \text{ for } A > 4.$$

These values are obtained in the Maxwell fluid case when $T \longrightarrow 0$, *i.e.* if the transit time is very long or the relaxation time is very short. The ratio

$$M = \frac{F_N}{F_M} = \frac{U\eta_{max} b}{h}\sqrt{\frac{\pi}{A}}\frac{h}{Gb^2Q}$$

Since $T = \frac{U\eta_{max}}{Gb}$, it follows that $M = \frac{T}{Q}\sqrt{\frac{\pi}{A}}$.

The value of M has been calculated over the range of T, and as $T \longrightarrow 0$, $M \longrightarrow 1$. As T, the relaxation number, gets very large, the solutions indicate that F_M becomes proportional to

$$\sqrt{\frac{\pi}{A}}\frac{b^2G}{h} \text{ or } F_M = k\sqrt{\frac{\pi}{A}}\frac{b^2G}{h}$$

Thus M becomes $\frac{U\eta_{max} b}{h}\sqrt{\frac{\pi}{A}}\frac{h}{kb^2G}\sqrt{\frac{A}{\pi}} = \frac{1}{k}$

and $\frac{1}{k} \approx 0{\cdot}4$ and thus $M \approx 0{\cdot}4T$ as $T \longrightarrow \infty$.

The values of M against T are shown in Fig 4. It appears that M only starts to diverge significantly from unity when $T \gtrsim 1$.

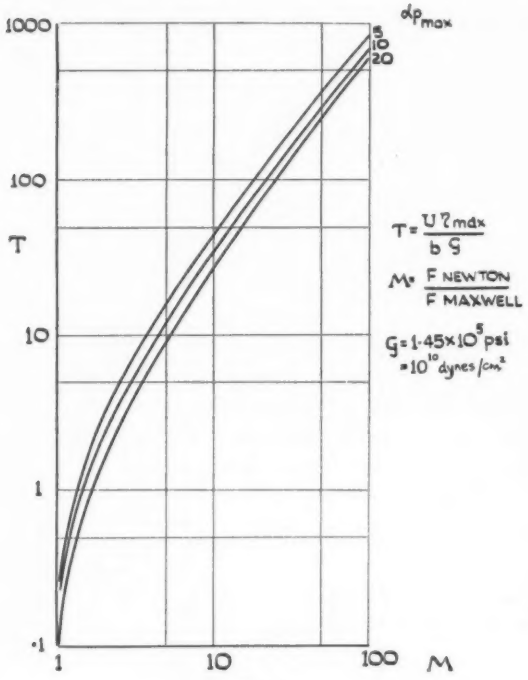

FIG 4

In the next section these results are applied to some work of Borsoff using fast running gears, the object being to see if the value of T in his system could reach unity. If this is so, then the visco-elastic properties of the fluid could play a part in explaining the results.

APPLICATION TO GEARS

In this paper by V. N. Borsoff on the mechanism of gear lubrication, scuffing loads were shown to rise as the speed increased beyond a certain value. In this section the theory developed here will be applied to these results. The author has very kindly furnished additional data to enable this to be done.

The theory so far has shown that visco-elasticity can come in only if $T \gtrsim 1$.

In his results the width of Hertzian contact and the transit time are listed for given oils and loads and speeds at the minimum scuffing load. At higher speeds the scuffing load was found to increase.

If it is assumed that this minimum load corresponds to the start of the visco-elastic effect, *i.e.* that at this point $T = 1$, then as

$$T = \frac{\eta_{max}/G}{\frac{1}{2} \times \text{transit time}} = 1$$

so $$\eta_{max} = \tfrac{1}{2} \text{ transit time} \times G.$$

Now $G = 10^{10}$ dynes/cm², and as the transit time is given η_{max} can be calculated. If the viscosity–pressure law is taken as $\eta_p = \eta_o e^{\alpha p}$, then η_p can be calculated if η_o is known. If it can be assumed that the flash temperature is 50° C, then a value for η_o can be obtained from Borsoff's results; hence, knowing p_{max}, α can be found. This can be compared with likely values of α.

As is usual in this work, everything comes to a halt at the barrier of ignorance of α.

All these various values can be tabulated. The first five columns are taken directly from Borsoff's data. The η_o is obtained assuming a 50° C temperature rise, and η_{max} is obtained from the relation

$$\eta_{max} = \tfrac{1}{2} \text{ transit time} \times G$$

whence the ratio η_{max}/η_o is $e^{\alpha p_{max}}$ and so the next column lists αp_{max}, *i.e.* $\log_e(\eta_{max}/\eta_o)$. Finally, dividing by p_{max} gives α calc:

Oil	Speed, rev/min	Contact width, inches	Tip transit time, sec	p_{max}, kg/cm²	η_o poises	$T = 1$ η_{max}, poise	αp_{max}	α_{calc}, $(kg/cm^2)^{-1}$	$\alpha_{Wooster}$ $(kg/cm^2)^{-1}$
1010	10,000	$2{\cdot}76 \times 10^{-3}$	$0{\cdot}76 \times 10^{-3}$	$4{\cdot}1 \times 10^{3}$	0·029	$1{\cdot}35 \times 10^{4}$	13·1	$2{\cdot}6 \times 10^{-3}$	$1{\cdot}06 \times 10^{-3}$
	15,000	3·91	0·25	5·8	0·029	1·25	13·1	2·6	1·06
10W	5,200	3·05	0·575	4·5	0·048	2·87	12·5	2·8	1·28
20	3,000	4·81	1·5	7·2	0·116	7·5	12·4	1·72	1·66
30	5,200	5·35	1·01	8·0	0·101	5·0	13·1	1·65	1·60
60	5,200	8·18	1·54	12·1	0·224	7·7	12·8	1·05	1·75

The correlation published by Wooster [9] is that $\alpha = [0{\cdot}6 + \log_{10}(100\eta_o)] \times 10^{-3}$, where η is viscosity in poises and α is in $(kg/cm^2)^{-1}$. The final column headed $\alpha_{Wooster}$ gives the pressure viscosity coefficient calculated by his method.

It is seen that α is of the right order of magnitude, but the trend is the reverse from what is expected. Usually α increases with an increase in viscosity. Here is decreases, though this could possibly be due to an incorrect choice of η_o.

The analysis of Grubin, quoted by Siripongse and Cameron shows that over at least 98 per cent of the

contact zone the oil film must be parallel, and the thickness of the film is decided in the 2 per cent of the contact zone at entry. Crook and Archard [10] have also shown experimentally that conditions at entry are of overriding importance. At this point the pressure p is

$p_{max}(1 - 0{\cdot}98^2)$ under a parabolic pressure distribution or

$p_{max}(1 - 0{\cdot}98^2)^{\frac{1}{2}}$ under an elliptical one, *i.e.* $p = p_{max}0{\cdot}04^{\frac{1}{2}} = 0{\cdot}2p_{max}$.

If αp_{max} is, say, 14 at the centre of the contact zone, and as $e^{14} = 1{\cdot}2 \times 10^6$, the viscosity has risen by this amount. At a point 0·98 from the centre, αp_{max} is only $0{\cdot}2 \times 14$ and $e^{2{\cdot}8} = 16{\cdot}4$, which is a factor of $3{\cdot}4 \times 10^5$ down. The half transit time would, of course, be divided by about 50, *i.e.* the time taken for an oil particle to travel from $x = -b$ to $x = -0{\cdot}98b$, as compared with the time required for it to move from $x = -b$ to $x = 0$ on the earlier analysis. This does not at all compensate for the drop in viscosity.

This tends to show that relaxation probably does not play a significant part in gear lubrication. The rise in scuffing load could well be due to the relative flattening-off of the viscosity–temperature curve at higher temperatures, so the product $\eta_0 U$, which determines the film formation, will start rising at high speeds.

This problem is now being studied at the City and Guilds College, and further results will be reported, it is hoped, in due course.

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OBITUARY

ARTHUR CLIFFORD HARTLEY, C.B.E.

1889–1960

THE death of Clifford Hartley on 28 January came as a great shock to his very wide circle of friends, for although he had been seriously ill for some three weeks, everyone had begun to hope that he was on the way to recovery.

He was elected a Member (later becoming a Fellow) of the Institute in March 1927, serving on the Council from 1934 to 1942, from 1953 to 1955, and from 1958 until his death. He was a Vice-President from 1942 to 1948, and also from 1955 to 1958; thus for over twenty years he took a very active part in the affairs of the Institute. In 1959 he was awarded the Redwood Medal for his outstanding contributions to the science and technology of petroleum.

Hartley was one of that band of engineers which was attracted into the petroleum industry in the years immediately following the first world war. The rapid increase in the demand for petroleum and its products, and the realization that a new major industry had come into being, coupled with the fact that recruitment into it had been held up by the war, resulted in a great demand by the petroleum industry for engineers capable of dealing with its unique problems. In 1924 Hartley joined the Anglo-Persian Oil Co as assistant manager in the Engineering Department, thus rejoining his wartime friend and colleague W. C. Mitchell, who was then assistant chief engineer. This was the beginning of his long association with the present British Petroleum Co. In 1934 he was appointed chief engineer of the Company, and remained in that important position until his retirement in 1951. For a man like Hartley, however, the thought of real retirement could never enter his mind; he proceeded to build up a very extensive private practice and also became a consultant to Messrs Rendel, Palmer, and Tritton. His especial interests were pipelines and the handling of petroleum, and he developed and perfected an entirely new method of loading tankers at sea terminals.

Born in Hull on 7 January 1889, Hartley began his engineering education at the Technical College of that city in 1906 and proceeded later to the Imperial College of Science and Technology, London, where he obtained his A.C.G.I., and B.Sc.(Eng) with honours in 1910. During the following five years he gained a wide experience in both civil and mechanical engineering, becoming an associate member of the Institutions of Civil and Mechanical Engineers in 1916. In that year he joined the Royal Flying Corps, where his special aptitude for the practical solution of engineering problems showed in his development of the Constantinescu synchronizing gear, which enabled machine guns in aircraft to fire between the blades of rotating propellers. For his services in the R.F.C. he was awarded the O.B.E.

During the second world war he was lent by his company to H.M. Government, and in 1940 was concerned with the development of a stabilized automatic bomb sight. In 1942 he was largely responsible for the development of PLUTO, the submarine pipelines which were later used across the English Channel. In the latter part of 1942 he was appointed technical director of the Petroleum Warfare Department, and afterwards was responsible for the development of FIDO, the airfield fog clearance system, and for flame weapons. He was appointed C.B.E. in 1944 for his wartime services, and was awarded the United States Medal of Freedom in 1946.

In 1951 he was elected President of the Institution of Mechanical Engineers, and was made an honorary member in 1956. In 1936 he was elected a Fellow of the City and Guilds of London Institute and in 1953 received the Honorary Fellowship of the Imperial College. In November 1959 he was elected President of the Institution of Civil Engineers, thus joining the select few who have been presidents of the two senior engineering institutions. At the time of his death he was Chairman of the Oil Industries Club.

Clifford Hartley had come to be recognized as one of the leading members of his profession, and by his death not only the petroleum industry but engineering as a whole has suffered a very great loss. His connexion with PLUTO and FIDO ensures him a place in the history of the second world war, but his work on the oilfields, pipelines, and refineries of the Middle East are monuments to his memory. H.S.G.